Institut für Physikalische Elektronik

Institute of Physical Electronics

Universität Stuttgart

Jahresbericht

Annual Report

2001

Institut für Physikalische Elektronik
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Inhaltsverzeichnis / *Table of Contents*

1 Vorwort

Liebe Freunde des *ipe*,

dieser Jahresbericht gibt Ihnen wieder einen Ausschnitt aus unseren Aktivitäten. Auch im Jahr 2001 haben wir innerhalb des *ipe* und hat sich um das *ipe* herum einiges verändert. So läuft zum Beispiel zur Zeit unter dem Namen „100-online“ eine Offensive zur Modernisierung der Lehre der Universität – mehr als 100 Vorlesungen sollen ins Internet gestellt werden. Im Rahmen dieser Offensive stellt das *ipe* zur Zeit sechs von sieben Vorlesungen komplett auf digitale Präsentationsformen um. Ab dem Ende des Sommersemesters 2002 sind diese Vorlesungen dann im Internet – zum grössten Teil in englischer Sprache – verfügbar. Der Aufwand an Zeit und Technik bei der Umstellung dieser Vorlesungen ist hoch, aber er wird sich mittelfristig mit Sicherheit in einer noch besseren Qualität der Lehre des *ipe* niederschlagen. Hierzu werden auch die zwei neuen Fachpraktika „Photovoltaik“ und „Bauelement- und Mikrochiptechnologie“ beitragen, die wir ab Sommersemester 2002 anbieten.

Im Verlauf des Jahres 2002 wird die Fakultät „Elektrotechnik und Informationstechnik“ aufgelöst. Um die Vorgabe des Wissenschaftsministeriums von mindestens 20 Professoren innerhalb einer Fakultät zu erfüllen, fusionieren wir mit der jetzigen Fakultät „Informatik“; beide Fakultäten (mit weit mehr als 2000 Studenten!) werden durch diese Fusion gestärkt.

Auch innerhalb des *ipe* gab es einige Veränderungen. Wenn Sie unsere neue Struktur auf der letzten Umschlagseite ansehen, dann werden Sie entdecken, dass die Abteilungen „Bildverarbeitung“ und „Brennstoffzellen“ geschlossen sind. Stattdessen haben wir uns auf der Seite der Halbleitertechnologie neu formiert und die Verantwortlichkeiten umverteilt. Seit unser Privatdozent und Gruppenleiter Ralf Bergmann eine attraktive Position als Abteilungsleiter in der Forschung der Firma Bosch angenommen hat, leitet Markus Schubert unsere gesamten Silicium-Aktivitäten am „amorphen Si“ und „kristallinen Si“. Zu seiner Unterstützung haben wir eine „Si-Technologie“ geschaffen, die ab sofort von Thomas Wagner angeführt wird. In ähnlicher Weise zeichnet unser know-how-Träger Gerhard Bilger neben der früheren „Oberflächenanalyse“ jetzt auch für die Organisation der „CIS-

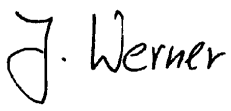
Technologie“ verantwortlich. Peter Schwarzmann baut eine Gruppe „Systeme“ auf.

Am erfreulichsten von der Personalentwicklung her ist es, dass sich zwei ehemalige Doktoranden, Christian Koch und Titus Rinke, selbständig gemacht haben. Wir alle wünschen der Firma unserer Jungunternehmer, die zum Teil auf am *ipe* entstandenen Patenten basiert, viel Erfolg!

Seit ein paar Monaten gibt es am *ipe* eine von Markus Schubert und mir selbst angeführte Gruppe von äusserst aktiven, jungen Studenten, welche die Integration von Photovoltaik in Kleidung erprobt; im Bericht von Christian Gemmer können Sie erste Ergebnisse nachlesen. Innerhalb dieser Arbeiten ist das Markenzeichen „integrierte Photovoltaik, *ipv*“ entstanden. Hier sind eventuell neue Märkte für die Photovoltaik erschliessbar.

Die Struktur und Aufgabe der Universität und des *ipe* bringt es mit sich, dass wir im wesentlichen nur eine Konstante haben: die permanente Weiterentwicklung und Veränderung. Stillstand können wir uns nicht leisten! Hierzu gehört auch, dass gerade Leistungsträger wie Ralf Bergmann und unsere „Zauber-Sekretärin“ Inge Zaiser das *ipe* verlassen, um die nächste Stufe ihrer beruflichen Karriereleiter zu erklimmen. Die beiden werden mit Sicherheit viel Erfolg haben bei ihren neuen Aufgaben bei Bosch bzw. der Europäischen Kommission. Ich danke den beiden und allen anderen Mitarbeiterinnen und Mitarbeitern für ihre erstklassige Leistung am *ipe* in Forschung, Lehre und Personalförderung im Jahr 2001.

Stuttgart, Dezember 2001



Jürgen H. Werner

Preface

Dear friends of the *ipe*,

this annual report presents a part of our activities during the last year. In 2001, several things around and within the *ipe* have changed or were actively changed by us. The University of Stuttgart, as a whole, started, for example, the initiative“100-online” to put more than 100 lectures into the internet. Within this initiative, the *ipe* tranforms six of seven lectures into digitally presentable form. At the end of the summer term 2002, these lectures will be available in the internet. Most of these lectures are in (Swabian) English. The expenditure of time and technology is high. However, on the long run, it will pay off by an even better quality of the teaching performed by the *ipe.* Two new courses on practical laboratory work in “Photovoltaics“ and “Device and Microchip Technology“ will contribute to this task; these courses will start with the summer term 2002.

During the year 2002, our present Faculty “Electrical Engineering and Information Technology” will merge with the former Faculty “Computer Science”. By these means, we will fulfill the regulation of our ministry to construct faculties with more than 20 professors. Both formerly separate faculties (with much more than 2000 students!) will be stronger after this merging process.

Within the *ipe,* there were several changes as well. If you have a look at our new structure on the back side of this report, then you will realize that the groups “Image Processing” and “Fuel Cells” have been closed. Instead, we will concentrate on strengthening our semiconductor technology. Since Ralf Bergmann left us to accept an attractive management position in the research department of Bosch, Markus Schubert leads all of our silicon acitivities on “Amorphous Si” as well as on “Crystalline Si”. He is supported by a “Si-Technology” group led by Thomas Wagner. Similarly, Gerhard Bilger is now not only responsibe for the former “Surface Analysis” but also for the whole “CIS-Technology”. Peter Schwarzmann builds up a group “Systems”.

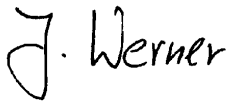
From the point of view of personnel development, it is most pleasurable that two former “Doktoranden” became entrepreneurs. All

of us wish the best for their company, which is partly based on patents written during their time within the *ipe*.

A few months ago, Markus Schubert and myself started a project on "photovoltaics integrated into clothes" together with a group of very active young students. The report of Christian Gemmer gives first results. We established the trade mark "integrated photovoltaics, *ipv*" which is derived from our institute logo. New markets for photovoltaics may be opened in this field.

The structure and the tasks of our university as well as of the *ipe* contain essentially only one constant: permanent change and development. We cannot afford standing still! As a natural consequence, also top performers as Ralf Bergmann and our "magic secretary" Inge Zaiser leave the *ipe* to climb up the next step on the ladder of their professional career. I am sure, that both of them will be successful in their new positions at Bosch, respectively the European Commission. I am grateful to both of them as well as to all coworkers of the *ipe* for their first class performance in research, teaching, and personnel development of the *ipe* in 2001.

Stuttgart, December 2001



Jürgen H. Werner

2 Lehre am *ipe*

2.1 Vorlesung *Bauelemente der Mikroelektronik I*

Einführung: Informationen; Lehrbuch; Kontakt, das Institut für Physikalische Elektronik; Geschichte der Mikroelektronik; Mikroelektronik heute.
Grundlegende Eigenschaften von Halbleitern: Spezifischer Widerstand; Energiebänder; Messung der Bandlücke; Silicium für die Mikroelektronik; Dotieren von Silicium; das Loch als Quasiteilchen; Energien von Elektronen und Löchern; effektive Massen m*; Leitfähigkeit σ; Konzentration von Ladungsträgern in den Bänden; Elektronen und Löcherströme; Nichtgleichgewichtszustände.
Elektrostatik des pn-Übergangs: Raumladungszone, Kapazität.
Ströme im pn-Übergang: Minoritätsträgerinjektion; Strom/Spannungskennline; Kleinsignalverhalten.
Spezielle Halbleiterdioden: Photodioden, Solarzellen, Leuchtdioden, Halbleiterlaser.

2.2 Vorlesung *Festkörperelektronik*

Das freie Elektron als Teilchen und als Welle: Teilcheneigenschaften; Welleneigenschaften, Bragg-Bedingung, de-Broglie-Beziehung; Strukturanalyse, LEED.
Die Schrödinger-Gleichung und einige Anwendungen für das freie Elektron: Statistische Deutung der de-Broglie-Wellen, Elektronen in Potentialtöpfen und im Potentialgitter, Fermiverteilung.
Elektronische Bänder in Festkörpern: Reziprokes Gitter, Elektronen im periodischen Potential (Blochwellen, Kronig-Penney-Modell, bewegte Elektronen), effektive Masse, Bandstrukturen wichtiger Halbleiter, Bändermodell, Lochkonzept.
Halbleiter im Bändermodell: Isolatoren, Halbleiter, Metalle; Besetzung der Bänder; elektrostatisches Potential des Halbleiters; Fermi-Niveau im Gleichgewicht
Ströme in Halbleitern: Feldstrom und Diffusionsstrom, Gesamtstrom, Ströme und Gradienten der Quasi-Fermi-Niveaus.
Austritt von Elektronen aus Metallen und Halbleitern: Austrittsarbeit, thermische Emission, Feldemission (Feldelektronenmikroskop, Rastertunnelmikroskop), Photoemission (äußerer Photoeffekt), Sekundärelektronen-Emission (Rasterelektronenmikroskop).
Der Schottky-Kontakt: Barrierenbildung, Ausbildung der Raumladungszone; Bändermodell; Anlegen von Spannungen, Kennlinie, Bestimmung der Schottky-Barriere, Ohmsche Kontakte.

2.3 Vorlesung *Optoelectronic Devices and Systems I* **(englisch gehalten / *in English*)**

Introduction – What is optoelectronics? Overlap of optoelectronics with classic areas; optical regime; scheme of an optical communication system; what is light?

Basic Physics: Simple equations: reflectance, absorbance, transmittance; refraction and total internal reflection; reflectance r_F, transmittance t_F for $Q_i = 0$

Thermal Radiation: Black body radiation (Kirchhoff's radiation law, Planck's radiation law, Wien's displacement law, Stefan-Boltzmann law); grey body radiation; selective body radiation of a semiconductor.

Coherence: Definition; length of a wavetrain; the frequency spectrum of a wavetrain

Semiconductor Basics: Energy bands and Fermi function (the wave vector *k*, the band structure *E(k)*, limited range of *k*-values, the Brillouin zone, crystal momentum p_k, impulse p_e, direct and indirect bandgap semiconductors).

Excitation and Recombination Processes in Semiconductors: Introduction – What is luminescence? Absorption of radiation in semiconductors; carrier recombination in semiconductors.

Light emitting diodes: Working principle; the emitted spectrum of an LED; materials for LEDs (and lasers); emission efficiency of LEDs.

Semiconductor Lasers: Working principle; laser components; ratio of induced (stimulated) to spontaneous emission; gain of a laser (first general laser condition); the resonator (second general lasing condition); first lasing condition for semiconductor lasers; second lasing condition for a semiconductor laser; heterojunctions, heterostructures; light guiding in semiconductor lasers; stripe contact laser; laser modes; the gain in a semiconductor laser; modern semiconductor lasers.

Glass Fibres: Advantages of glass fibers; fiber configurations; step-index fibers; graded-index fibres; mono-mode fibers; dispersion in glass fibers; attenuation in glass fibers

Photodetectors: Introduction, general considerations; properties and specifications of photodetectors; photoconductors; photodiodes; photodiodes with internal gain: avalanche photodiodes (APDs); materials and detector configurations.

2.4 Vorlesung *Photovoltaik*

Energiewirtschaft: Umrechnungstabelle; Energieumsatz in Deutschland und weltweit; Vorräte und Reichweite fossiler Energieträger; CO_2-Erzeugung und Treibhauseffekt.

Potential der Sonnenstrahlung: Theoretische und technische Potentiale für Primärenergie und für Stromerzeugung in Deutschland, Flächenbedarf

Solarspektrum: Planck'sches Strahlungsgesetz, Wien'sches Verschiebungsgesetz, der AM-Wert.

Grundlagen der Photovoltaik: Absorption von Licht in Halbleitern; Mechanismen der Rekombination von Ladungsträgern (Verlustprozesse).

Grundgleichungen der Halbleiterbauelemente: Feld- und Diffusionsströme, Ströme und Quasi-Fermi-Niveaus; Poisson-Gleichung, Kontinuitätsgleichung; der pn-Übergang.

Solarzellen: Kenngrößen und Ersatzschaltbild, Oberflächenrekombination; maximale Wirkungsgrade: experimentelle Werte, theoretische Obergrenzen.

Zelltechnologien des kristallinen Siliziums: Herstellung von einkristallinem und grobkristallinem Si; Blockgießen, Folienprozesse; Siebdrucktechnik = heutige Standardtechnologie für Zellen, Technologie von Hocheffizienz-Zellen.

Solarzellen aus amorphem Silizium: Warum dünne Schichten? Eigenschaften von amorphem Si; Aufbau und Herstellung von a-Si Solarzellen; Anwendungen / Marktlage.

Solarzellen aus Verbindungshalbleitern: Materialaspekte; Herstellungsverfahren für Halbleiterschichten; CdTe und $CuInSe_2$; Solarzellenstrukturen, spektrale Quantenausbeute.

2.5 Vorlesung *Energiewandlung*

Einführung: Energieformen, Energieeinheiten; Energiewandlungsprozesse; Energieträger und Ressourcen, Energieverbrauch und Nutzungsarten; Umweltprobleme.

Physikalische Grundlagen: Phänomenologische Thermodynamik (Zustandsgrößen und Zustandsänderungen, Hauptsätze, Kreisprozesse, technische Prozesse); Kernphysik (Kernspaltung, Kernfusion).

Regenerative Energiequellen: Grundlagen (Sonnenspektrum, Planckscher Strahler, Einstrahlungsbedingungen, Konzentration), direkte Nutzung der Sonnenenergie (Solarthermie mit Nieder- und Hochtemperaturprozessen, Photovoltaik mit Lichtabsorption, Materialauswahl, Solarzellenaufbau und Technik photovoltaischer Systeme), indirekte Nutzung der Sonnenenergie (Wasserkraft, Windenergie).

Chemische Speicherung elektrischer Energie: Wasserstofftechnik (Elektrolyse, Wasserstoff-Kreislauf), Methanol als Energieträger (Synthese aus CO_2, Energiebilanz), Brennstoffzellen (Elektrochemische Grundlagen, Energiebilanz, Bauformen wie PAFC, MCFC, SOFC, PEMFC, DMFC, Anwendung im Fahrzeug und in Blockheizkraftwerken), Batterien (Bleiakkumulator, Natrium-Schwefel- und Natrium-Nickelchlorid-Batterie, Zink-Luft-Batterie, Nickel-Metallhydrid-Akku, Lithium-Batteriesysteme).

2.6 Vorlesung *Laser- und Strahlungsquellen*

Licht und Farbe: Hellempfindlichkeit des Auges; Einführung in die Farbmetrik: Normspektralwerte, Farbdreieck.

Das Auge: Innerer Aufbau, Fehlsichtigkeit.

Strahlungsmessung/Detektoren: Thermische Detektoren, Quantendetektoren.

Thermische Strahler: Grundlagen, Planck'scher Strahler, Glühlampen, Halogenglühlampen.

Gasentladungsstrahler: Grundlagen, Hochdruck- und Niederdruck-Gasentladungsstrahler, Leuchtstofflampen.

Leuchtdioden: Klassische Halbleitermaterialien, blaue Leuchtdioden (GaN).

Organische Leuchtdioden: Grundlagen, Materialien.
Laser I: Grundlagen, Q-switch, Modenkopplung, Frequenzverdopplung.
Laser II: Nicht-Halbleiterlaser: Festkörperlaser, Gaslaser, Farbstofflaser.
Laser III: Halbleiterlaser.
Laseranwendungen: Laser als Werkzeug, Laserkristallisation, Einsatz in elektronischen Geräten.
Displays: Grundlagen, Aktiv-Matrix LCD-Displays, EL-Displays, Plasma-Displays.

2.7 Vorlesung *Thin Film Characterization Methods* (PD Dr. R. B. Bergmann) (englisch gehalten / *in English*)

Introduction: Current questions, problems and challenges of semiconductor characterization; structural, electrical and optical material characterization in the semiconductor industry.
Structural Characterization: Characterization of the semiconductor volume: optical microscopy, (transmission) electron microscopy, defect etching, X-ray diffraction techniques; Characterization of semiconductor surfaces: surface reconstruction, surface electron diffraction methods (RHEED, LEED), atomic force microscopy (AFM).
Electrical Characterization: Measurement of majority carrier properties: two and four point probe measurement, spreading resistance, hot probe, Hall-Effect, capacitance-voltage measurements (CV), Deep Level Transient Spectroscopy (DLTS); Measurement of minority carrier properties: recombination rate after Shockley-Read-Hall theory, static methods (photoconductivity, quantum efficiency), dynamic methods (carrier decay, current transients).
Optical Characterization: Optical absorption and emission in semiconductors; Transmission and reflection measurements, ellipsometry, photoluminescence, Raman spectroscopy.

2.8 Vorlesung *Digitale Bildverarbeitung* (Lehrbeauftragter Dr. R. Ott)

Bildentstehung: Behandlung der Abtastung von Bildern mit Methoden der zweidimensionalen nichtkausalen Systemtheorie; Bildarten aus der Medizin, aus der technischen Qualitätskontrolle und aus der Fernerkundung.
Bildverarbeitung: Lineare und nichtlineare Bildfilter, morphologische Filter; Kennlinientransformation, Bildverbesserung.
Bildmerkmale: Definition von Bildmerkmalen (ikonische Merkmale, syntaktische Merkmale), Bewertung von Bildmerkmalen anhand der Aufgabenstellung; Merkmale bezüglich der Morphologie und der Farbe; Deskriptoren für Bilder und Graphen.
Mustererkennung: Klassifikation von Objekten anhand hochdimensionaler Merkmalssätze mit den Methoden der statistischen Klassifikatoren (Fisher-Diskriminanzanalyse, Polynomklassifikatoren), mit den Methoden der künstlichen neuronalen Netze und mit modellbasierten Ansätzen.
Begleitendes Material: Ergänzung der Vorlesungsinhalte durch Demonstrationen und Bildmaterial aus der industriellen Meß- und Prüftechnik sowie der automatischen Fahrzeugführung.

2.9 Praktika:

Grundlagenpraktikum *Physikalische Elektronik* : im Vorstudium, WS + SS

5 Versuche: LED, Thermoelektrik, Farbfernsehtechnik, Digitale Bildverarbeitung, Photovoltaik und Netzeinspeisung.

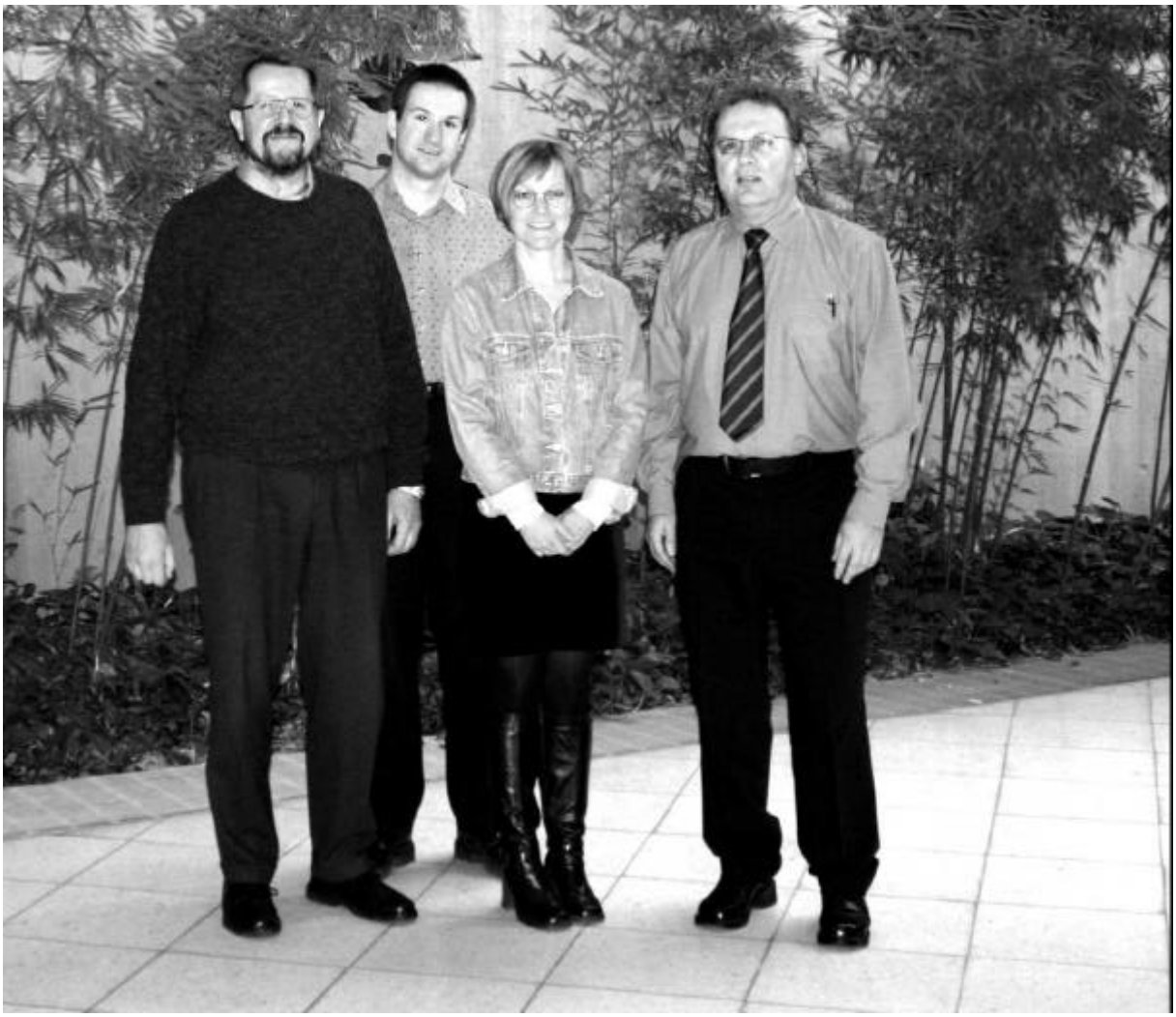
Praktikum *Elektrophysik* : im Hauptstudium, SS

(mit Inst. f. Plasmaforschung)

7 Versuche: Mustererkennung in der digitalen Bildverarbeitung (1fach), Halbleiterlaser und optische Signalübertragung (1fach), Solarzellen: Technologie; Kennlinie und Quantenausbeute; Struktur; Materialanalyse (3fach), Hochvakuum- und Dünnschichttechnik: Vakuumpumpen und Pumpsysteme; Aufdampfung und Schichtdickenmessung (1fach).

3 Menschen am *ipe* / *People at the ipe*

3.1 Verwaltung und Institutsleitung / *Administration and Head of Institute*



Verwaltung und Institutsleitung / *Administration and the Head of Institute :*
Von links *(from left)* : Fritz Pfisterer, Werner Wille, Inge Zaiser, Jürgen Werner

3.2 Gruppe Silicium / *Group Silicon*

Gruppenleiter/Group Leader: MARKUS SCHUBERT
Mitarbeiter/Collaborators: Christopher Berge, Klaus Brenner, Kai Brühne, Xinmin Cao, Cecilia Craff-Castillo, Christian Gemmer, Jörg Glöckner, Christiane Köhler, Brigitte Lutz, Michail Rakhlin, Martin Rojahn, Thomas Wagner, Birgitt Winter

Die Arbeitsgruppe *Silicium* entwickelt Technologien zur Herstellung von Dünnschichtbauelementen auf Silicium-Basis. Wir stellen dünne, flexible Filme aus mono- und polykristallinem, mikro- und nanokristallinem sowie amorphem Silicium her. Im Mittelpunkt der Forschungs- und Entwicklungsaktivitäten steht die Anwendung in Solarzellen, insbesondere der Transfer dünner monokristalliner Zellen auf beliebige Fremdsubstrate, aber auch die Weiterentwicklung "proto-kristalliner" Solarzellen, die bei Temperaturen unter 100^{o}C direkt auf kostengünstigen Kunststoffsubstraten hergestellt werden. Die Entwicklung von Solarzellen, die mit Hilfe "quasi-monokristalliner" Schichten zunächst auf Glassubstrate transferiert wurden, konnte in diesem Jahr verschiedene Wirkungsgradrekorde ans *ipe* holen. Die Kombination von Dünnschichttechnik, lithographischer Strukturierung und Mikroelektronik für Photodioden, Transistoren und verschiedene Sensoranwendungen bietet ein weites Betätigungsfeld. Positionssensoren und "Thin-Film-on-CMOS"-Kameras sind bereits erfolgreiche Beispiele, Thermosensoren und transferierbare, strahlungsharte Dünnschicht-CMOS-Schaltungen sind in der Entwicklung.

The *silicon* work group explores technologies for thin-film devices on the basis of silicon in its various modifications. We deposit or generate thin and flexible films consisting of mono- or polycrystalline, micro- or nanocrystalline, as well as amorphous silicon. The main focus of our activities in research and development is on photovoltaic applications, especially on the transfer of thin, monocrystalline solar cells onto arbitrary foreign substrates. Another important field is the improvement of 'protocrystalline' cells which are directly deposited on very cost-effective plastic substrates like PET. Monocrystalline Si thin-film solar cells which had been transferred to glass substrates with the help of our 'quasi-monocrystalline' layers demonstrated independently confirmed world record conversion efficiencies. Combining thin-film technology, lithography and microelectronics for devices like photodiodes, transistors, and various sensors, opens a wide field of action. We successfully demonstrate advanced position sensors and 'Thin-Film-on-CMOS'-cameras, while thermosensors and transferable, radiation-hard thin-film CMOS circuits are still under development.

Gruppe Silicium / *Group Silicon:* Von links *(from left)* : Christiane Köhler, Xinmin Cao, Thomas Wagner , Brigitte Lutz, Christian Gemmer, Birgitt Winter, Martin Rojahn, Cecilia Craff-Castillo, Kai Brühne, Jörg Glöckner, Markus Schubert, Michail Rakhlin, Christopher Berge (nicht abgebildet / *not present*: Klaus Brenner).

3.3 Gruppe Verbindungshalbleiterschichten / *Group Compound Film Semiconductors (CIS)*

Gruppenleiter/Group Leader: HANS-WERNER SCHOCK
Mitarbeiter/Collaborators: Olena Chernykh, Kerstin Gebhardt, George Hanna, Martin Hartmann, Immo Kötschau, Nazar Kovtun, Victor Laptev, Kay Orgassa, Nguyen Hong Quang, Holm Wiesner.

Die Gruppe *Verbindungshalbleiterschichten* entwickelt vor allem Dünnschichtsolarzellen mit Heterostrukturen aus ternären Halbleiterverbindungen wie $CuInSe_2$ und verwandten Materialien als Absorberschichten und ZnO als Fensterschicht. Herstellungsverfahren für die Dünnschichten sind eigens hierfür entwickelte Aufdampf- und Sputterprozesse, sowie Abscheidungen aus chemischen Lösungen. Hilfsmittel zur Analyse der Schichten und der Heterostrukturen sind Photoelektronenspektroskopie, Rasterelektronen- und Rasterkraft-mikroskopie sowie Röntgenspektroskopie und Röntgenbeugung. Entwicklungsziele sind die Steigerung der Effizienz der Solarzellen auf 20%, die Weiterentwicklung von Solarzellen aus Verbindungen mit Bandabständen größer als 1,3 eV und entsprechend hoher Leerlaufspannung, die Optimierung von Cd-freien Frontelektroden und darüber hinaus strahlungsbeständige Dünnschichtsolarzellen mit geringem Gewicht für die Raumfahrt. Forschungsthemen sind die generellen Eigenschaften von komplexen Verbindungshalbleitern, insbesondere die Zusammenhänge zwischen Eigendefekten, Verunreinigungen und elektrischen und optischen Eigenschaften.

The *Compound Film Semiconductors (CIS)* group mainly investigates thin-film solar cells based on ternary compound semiconductors such as $CuInSe_2$ and related compounds. For the deposition of thin films, special coevaporation and sputtering processes as well as chemical processes are designed. Main tools for the optimization of heterostructures are photoelectron spectroscopy, scanning electron microscopy, atomic force microscopy as well as X-ray spectroscopy and X-ray diffraction. Goals of the developments are solar cells with an efficiency of about 20 %, the improvement of solar cells with band gaps in excess of 1.3 eV for high-voltage cells, the optimization of Cd-free front electrodes and furthermore radiation resistant, lightweight solar cells for space applications. Topics for research are the general properties of complex compound semiconductors, in particular the relations between native defects, impurities, and the electrical and optical properties.

Gruppe Verbindungshalbleiterschichten / *Group Compound Film Semiconductors:*
Von links *(from left)* : Victor Laptev, Nazar Kovtun, Olena Chernykh, Martin Hartmann
George Hanna, Nguyen Hong Quang, Hans-Werner Schock, Kerstin Gebhardt,
Kay Orgassa (nicht abgebildet / *not present:* Immo Kötschau, Holm Wiesner,
Mohammed Balboul)

3.4 Gruppe Systemtechnik und Lehrsysteme / *Group Systems Technology and Multi Media Teaching*

Gruppenleiter/Group Leader: PETER SCHWARZMANN
Mitarbeiter/Collaborator: Dieter Reismayr

Die Gruppe *Systemtechnik und Lehrsysteme* entsteht gegenwärtig neu am Institut. Sie befasst sich zum einen mit Systemeigenschaften regenerativer Energiewandlungssysteme und zum anderen mit der Einführung von Multimediawerkzeugen in die Ausbildung.

Die Integration der Systemtechnik in das Forschungs- und Bildungsspektrum des Instituts ist unabdingbar für Untersuchung und Dar--stellung des kompletten Systemverhaltens neuer Energiewandlungs-systeme.

Multimediawerkzeuge in der Lehre versprechen einige Vorteile:

- bessere Nutzung der menschlichen Aufnahmefähigkeit,
- neue Möglichkeiten der Nacharbeit von Vorlesungsstoff,
- erweiterte Möglichkeiten des Selbststudiums und
- Erstellung von Lehreinheiten für die Fort- und Weiterbildung von bereits berufstätigen Personen.

The group S*ystems Technology and Multi Media Teaching* has recently been installed at the Institute. One of its functions is to investigate properties of conversion systems for renewable energy, another purpose will be the introduction of multimedia tools into education.

The integration of systems technology into the research and education spectrum of the institute is indispensible for investigation and presentation of the complete system of new energy conversion systems.

The introduction of multi media tools into education aims at several advantages:

- Optimized utilization of the human receptivity of students during lectures,
- New possibilities for students to work on past lectures,
- Improved facilities for self-instruction,
- Preparation of lessons for continuing education of professionals.

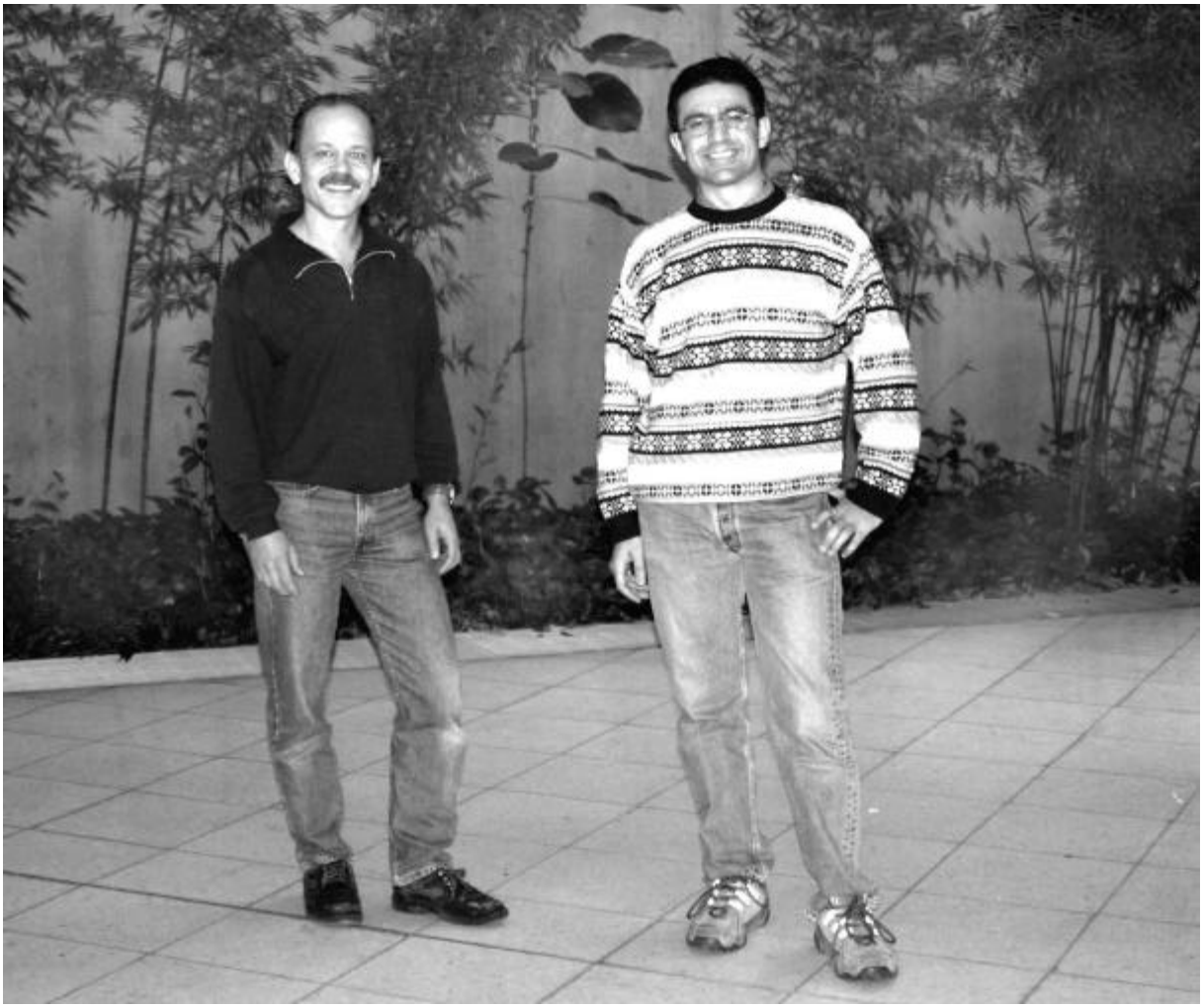
Gruppe Systemtechnik und Lehrsysteme /
Group Systems Technology and Multi Media Teaching :
Von links *(from left)* : Dieter Reismayr, Peter Schwarzmann

3.5 Gruppe Laserprozesse / *Group Laser Processing*

Gruppenleiter/Group Leader: Jürgen R. Köhler
Mitarbeiter/Collaborator: Jakob Demir

Die Gruppe *Laserprozesse* entwickelt neue Technologien zur Laserprozessierung von am *ipe* hergestellten Dünnschichthalbleitern. Hierzu zählen sowohl die Strukturierung der Halbleiterschichten als auch deren Kristallisation. Im Vordergrund unserer Arbeiten steht z. Zt. die Laserkristallisation amorpher Siliciumschichten auf Glassubstraten. Diese werden nach der Laserkristallisation zur Herstellung von Dünnfilmtransistoren verwendet, welche ihre Anwendung als Halbleiterbauelemente sowohl in Aktiv-Matrix adressierten Flüssigkristall-Bildschirmen als auch in selbstleuchtenden Bildschirmen auf der Basis organischer Leuchtdioden finden. Im Rahmen einer internationalen Kooperation ist es uns gelungen, die in den letzten Jahren etablierte Technologie unter Verwendung von Festkörperlasern weiter zu verbessern. Die gleichzeitige Kristallisation der hochdotierten Drain- und Source-Schichten zusammen mit der intrinsischen Kanal-Schicht resultiert in einer Erhöhung der Kanalbeweglichkeiten um ca. 10%. Ein weiterer Schwerpunkt bildet die Charakterisierung polykristalliner Siliciumschichten. In Zusammenarbeit mit der Universität Erlangen konnten wir nachweisen, daß sich die Textur der polykristallinen Silicium-Schicht durch die Silicium-Schichtdicke, die verwendete Pufferschicht und die Pulsfrequenz des Lasers definiert einstellen läßt.

The *laser processing* group explores new technologies for laser processing of thin film semiconductors. Examples are laser structuring, laser annealing and laser crystallization. Laser crystallization of thin-film silicon on glass is our most important application. Our laser crystallized polycrystalline silicon films are used for the fabrication of thin-film transistors, with possible applications in active matrix liquid crystal displays and displays based on organic light emitting diodes. A further improvement of our laser crystallization technology using all-solid-state lasers results in an increase of the channel mobilities of thin-film transistors by approximately 10%. Here we utilize the crystallization of drain, source and channel layers in only one processing step. We characterize our polycrystalline silicon films in collaboration with the University of Erlangen. As one result, we proved a strong dependence of the surface texture of the polycrystalline silicon films, which can be controlled by the silicon layer thickness, the buffer layer material, and the repetition frequency of the laser pulses.



Gruppe Laserprozesse / *Group Laser Processing :*
Von links *(from left)* : Jürgen Köhler, Jakob Demir.

3.6 Gruppe CIS-Technologie und Oberflächenanalyse / *Group CIS Technology and Surface Analysis*

Gruppenleiter/Groupleader: GERHARD BILGER
Mitarbeiter/Collaborators: Leo Bauer, Thomas Dolch, Vitali Emelianov, Peter Grabitz, Denis Kühnle, Viktor Laptev

Die bei der *Oberflächenanalyse* angewandten Methoden sind die Sekundärionen-Massenspektrometrie (SIMS) sowie die Röntgen- und Ultraviolett-Photoelektronen-Spektrometrie (XPS, UPS). Die Analytik unterstützt die Gruppen, die Forschung und Entwicklung an Materialien für die Photovoltaik und Sensorik am *ipe* betreiben. Nach außen werden diese Analytikmethoden als Dienstleistungen für die Industrie und andere Institute angeboten. Als sehr empfindliche Methode weist SIMS alle Elemente und deren Verbindungen bis in den ppb-Bereich nach. Tiefen- und ortsaufgelöste Analysen zeigen den Verlauf von Elementverteilungen in einer Schichtfolge und/oder deren laterale Verteilung. XPS-Analysen, empfindlich bis in den 0,1 Atom%-Bereich, sind quantitativ und geben Auskunft über Bindungszustände der Elemente. Die extrem oberflächensensitive Methode weist noch Oberflächenbedeckungen von 1/10 einer Monolage nach. Mit UPS wird die Valenzbandstruktur von Festkörpern untersucht. Bei der *CIS Technologie* liegt die Verantwortung für die Durchführung routinemäßiger Schichtpräparationen und den Unterhalt der dafür notwendigen Infrastruktur.

For *Surface Analysis* the methods applied are Secondary Ion Mass Spectrometry (SIMS), X-ray- and Ultraviolet-Photoelectron Spectrometry (XPS, UPS). These methods support the work of the groups at the Institute of Physical Electronics involved in research and development of materials for photovoltaics and sensors. Analyses are also offered as a service to other institutes and to industry as well. The method SIMS is very sensitive to the detection of all elements and their compositions with concentrations down to the ppb region. SIMS detects the distribution of elements in layers laterally resolved and/or in their depth. The analysis technique XPS is quantitative down to a concentration of 0.1 atomic % and gives information about the chemical binding state. XPS detects surface coverages down to 1/10 of a monolayer. The method UPS is applied to study the structure of the valence band in solids. *CIS Technology* includes the routine preparation of $CuInSe_2$ thin films for solar cells and the maintenance of the infra structure necessary for it.

Gruppe CIS Technologie und Oberflächenanalyse / *Group CIS Technology and Surface Analysis:*
Von links *(from left)* : Leo Bauer, Thomas Dolch, Gerhard Bilger, Peter Grabitz, Victor Laptev, Dennis Kühnle.

3.7 Gruppe Bauelementanalyse / *Group Device Analysis*

Gruppenleiter/Group Leader: UWE RAU
Mitarbeiter/Collaborators: Axel Jasenek, Gregor Kron, Mohammed Mamor, Viet Nguyen, Nils Rennebarth, Kurt Taretto-Zeyen, Mircea Turcu, Kristin Weinert

Die Gruppe *Baualementanalyse* befaßt sich mit der elektrischen und optischen Charakterisierung sowie der numerischen Simulation von Solarzellen basierend auf CdS/Cu(In,Ga)Se_2 und a-Si:H/c-Si Heterostrukturen sowie von Farbstoff-Solarzellen auf der Basis von nano-porösem TiO_2. Ziel unserer Aktivitäten ist ein grundlegendes Verständnis der Funktionsweise dieser Baulemente, des Einflusses der Präparationsbedingungen und des Designs des Baulements auf seine Leistungsfähigkeit. Wir benutzen elektrische Analysemethoden wie Strom-Spannungsmessungen, Admittanzspektroskopie und Transienten-Spektroskopie tiefer Störstellen (DLTS). Messungen der internen Quantenausbeute und Photolumineszenz dienen zur Untersuchung der elektro-optischen Eigenschaften der Materialien. Die experimentellen Resultate werden mit quantitativen, numerischen wie analytischen, Modellen verglichen, um ein kohärentes Verständnis der Bauelemente zu erhalten.

The *device analysis* group is concerned with the electrical and optical characterization and with the numerical simulation of large-area electronic devices such as solar cells based CdS/Cu(In,Ga)Se_2 and a-Si:H/c-Si heterojunctions as well as dye-sensitized solar cells based on nano-porous TiO_2. We focus on a fundamental understanding of the working principle of these devices, the influence of preparation conditions and device design on the performance and, finally, on the improvement and optimization. Electrical analysis is performed with the help of current voltage measurements, admittance spectroscopy, Deep Level Transient Spectroscopy (DLTS), and similar methods. Electro-optical analysis comprises measurements of internal quantum efficiency, optical transmittance and reflectance, photoluminescence, etc. The quantitative and coherent interpretation of these experimental results requires detailed modelling and simulation.

Gruppe Bauelementanalyse / *Group Device Analysis :*
Von links *(from left)* : Mohammed Mamor, Axel Jasenek, Kristin Weinert, Kurt Taretto-Zeyen, Nils Rennebarth, Mircea Turcu, Gregor Kron, Uwe Rau (nicht abgebildet / *not present:* Viet Nguyen).

3.8 Werkstatt / *Mechanical Workshop*

Werkstatt / *Workshop :*
Von links *(from left)* : Frank Scheuermann, Anton Riß.

4 Wissenschaftliche Einzelbeiträge */*

Selected Scientific Contributions

4.1 Electron and Proton Irradiation Effects in Cu(In,Ga)Se_2 Solar Cells

Author: K. WEINERT
In collaboration with: U. Rau, A. Jasenek, H. W. Schock, J. H. Werner, M. Yakushev [1], B. Schattat [2], W. Bolse [2]

Solar cells based on Cu(In,Ga)Se_2 (CIGS) absorber layers have the highest conversion efficiency of all photovoltaic thin-film technologies. In addition to the possibility to prepare this material on low-weight and flexible substrates, the extraordinary high radiation resistance against proton and electron irradiation makes this type of solar cells attractive for space applications. However, the radiation response of these devices has to be carefully analyzed in order to predict their performance under space conditions.

First, we study the defect generation in CIGS solar cells by high-energy proton and electron irradiation theoretically. We describe the radiation damage by high-energy electrons with the formalism of McKinley and Feshbach [1]. From the displacement cross section of electrons in CIGS, we obtain the theoretical defect introduction rate for electron irradiation. The solid line in Fig. 1 depicts the calculated values for different electron energies, whereas Fig. 2 presents the energy dependence of the theoretical defect introduction rate for protons (open circles). Here, we use the Monte Carlo program TRIM [2] to calculate the distribution of displaced atoms in a CIGS film caused by proton irradiation. From the amount of generated Frenkel pairs per proton, we estimate the theoretical defect introduction rate. To simulate the proton radiation damage of a complete heterojunction solar cell, we include the ZnO window layer for the simulations in the low-energy range.

Our experiments [3] investigate the behavior of CIGS solar cells under high electron and proton irradiation, and we compare the results with the calculated defect introduction rates. We observe a loss of conversion efficiency after electron irradiation caused by a decrease of the open circuit voltage V_{OC}, whereas proton irradiation causes a degradation of all solar cell parameters. However, the most important factor limiting the conversion efficiency after proton irradiation is still the decrease of V_{OC}. By assuming that V_{OC} depends on carrier recombination via bulk defects in the CIGS absorber layer, we determine the defect

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[2] *Institut für Strahlenphysik, Universität Stuttgart*

introduction rate from the V_{OC} loss. Figures 1 and 2 show the experimental values for electron as well as for proton irradiation.

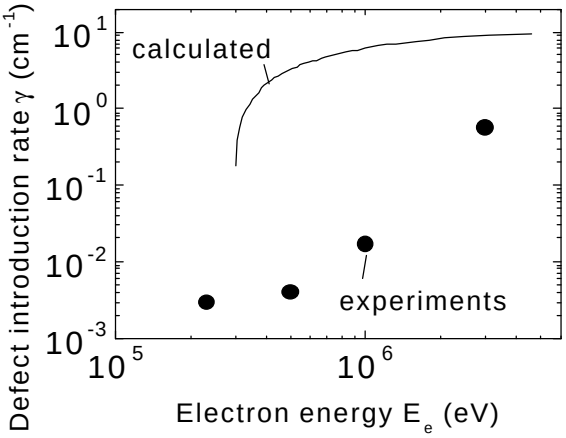

Figure 1: Defect introduction rate for electron irradiation: Theoretical values (solid line) calculated from the displacement cross section and experimental results (solid symbols).

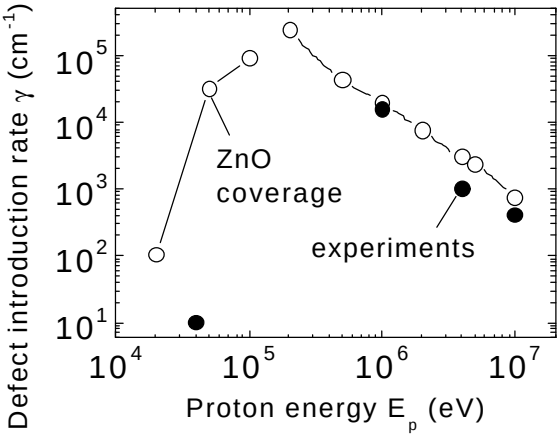

Figure 2: Defect introduction rate of protons in CIGS obtained by TRIM simulations (open symbols) and determined by irradiation experiments (solid symbols).

We find a good agreement between the experimental and theoretical defect introduction rates for proton irradiation, whereas the experimental and theoretical values for electron irradiation differ by at least two orders of magnitude. We explain this discrepancy by different damage processes under electron and proton irradiation. A single proton causes a cascade of hundreds of displacements in CIGS in a very small volume. Thus, proton irradiation generates locally isolated regions of high defect density. Because of the high concentration, the defects can interact and form stable defect complexes. Electrons cannot cause cascades because of their low momentum. Hence, electrons generate an uniform distribution of isolated defects. Less defect interaction takes place, and only a small part of the generated defects form complexes. Most of the radiation-induced Frenkel pairs recombine immediately after the generation and, consequently, are not detected in the measurements.

References:

[1] W. A. McKinley and H. Feshbach, Phys. Rev. **74**, 1759 (1948).

[2] J. F. ZIEGLER, J. P. BIERSACK, AND U. LITTMARK, The Stopping and Range of Ions in Solids, (Pergamon Press, New York, 1996).

[3] K. WEINERT, U. RAU, A. JASENEK, H. W. SCHOCK, J. H. WERNER, M. YAKUSHEV, B. SCHATTAT, AND W. BOLSE, in Proc. 17th Europ. Photov. Solar Energy Conf., in print.

4.2 Thermal annealing of defects in Cu(In,Ga)Se$_2$ after high-energy electron irradiation

Author: A. JASENEK
In collaboration with: K. Weinert, H. W. Schock, U. Rau, J. H. Werner

Thin film heterojunction solar cells with polycrystalline Cu(In,Ga)Se_2 (CIGS) absorber layers show an extraordinary radiation hardness [1] that makes them attractive for extraterrestrial applications. However, any prediction of the performance of solar cells in space has not only to account for defect *generation* under high-energy particle irradiation but also for the *annealing* of those defects under the working conditions of the devices. Consequently, the annealing behavior in the temperature range from 60 to 80 °C is of particular importance.

We investigate thermal annealing of Cu(In,Ga)Se_2 solar cells after 1-MeV electron irradiation with a typical fluence of 10^{18} cm^{-2}. To characterize the annealing kinetics, we perform *isochronal annealing* experiments in the following way [2]: Starting at room temperature, we anneal the samples for a fixed annealing time step Δt at temperatures which are successively increased by $\Delta T \approx 25$ K. Thus, the temperature at the nth annealing step is $T_n = 300\,\mathrm{K} + n\Delta T$. Between the annealing steps, we measure the solar cell output parameters. We repeat the procedure until reaching an annealing temperature sufficient to restore the initial efficiency.

Since after high-energy electron irradiation only the open circuit voltage V_{OC} degrades [1], it is sufficient to investigate the recovery of this quantity upon thermal annealing. Figure 1 displays the difference ΔV_{OC} between the open circuit voltage *prior* to irradiation and the actual V_{OC} *after* irradiation *and after* the different annealing steps at successively increased temperatures T_n. All solar cells in Fig. 1 lost about 100 mV by the irradiation with 1-MeV electrons (ΔV_{OC} at T = 300 K). The annealing of the cells, however, leads to a *full restoration* of the pre-irradiation value ($\Delta V_{OC} \approx 0$ mV at the highest temperatures).

As is seen from Fig. 1, the recovery step depends on the annealing time step Δt. By assuming that the annealing of the irradiation-induced recombination centers in Cu(In,Ga)Se_2 follows an exponential decay, we find that the annealing process is thermally activated with a decay time $\tau = \tau_0 \exp(E_a/kT)$, where the activation energy E_a is $E_a = 1.05 \pm 0.1$ eV and the pre-exponential factor is $\tau_0 = 10^{-10}$ s [2].

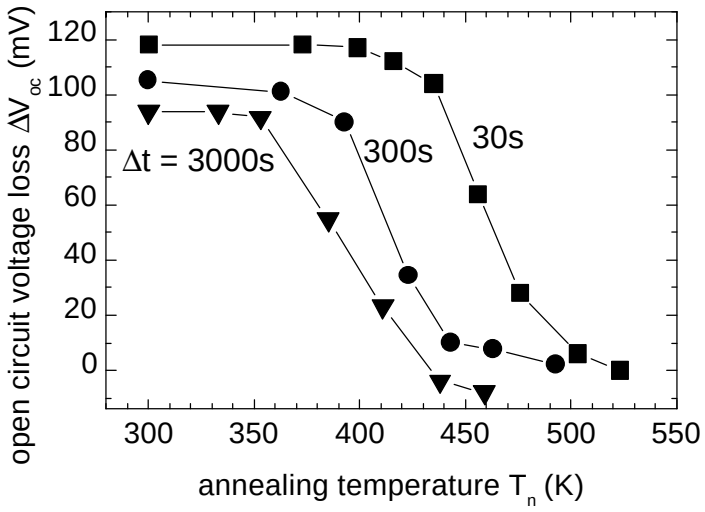

Figure 1 : The decrease of the open circuit voltage loss DV_{OC} towards zero with stepwise increased annealing temperature T_n shows that, after sufficient annealing, the devices completely recover from the radiation damage. The time steps Dt for the isochronal annealing experiments in air are Dt = 3000 s (triangles), 300 s (circles), and 30 s (squares).

From the above experiments we extrapolate a decay time constant $\tau = 2\times10^6$ s (i. e. about 1 month) [2,3] at a typical operating temperature of T = 330 K. Thus, the recovery time constant of $Cu(In,Ga)Se_2$ from the irradiation-induced generation of non-equilibrium defects is much shorter than the typical time span of a space mission. Therefore, the ability of the material to recover has to be considered in the prediction of the performance of $Cu(In,Ga)Se_2$ solar cells in space.

References:

[1] A. JASENEK AND U. RAU, J. Appl. Phys. **90**, 650 (2001).

[2] A. JASENEK, H. W. SCHOCK, J. H. WERNER, AND U. RAU, Appl. Phys. Lett **79**, 2922 (2001).

[3] U. Rau, A. Jasenek, K. Weinert, H. W. Schock, and J. H. Werner, in *Proc. 17th Europ. Photov. Solar Energy Conf.,* in print.

4.3 Trends of defect energies in the Cu(In,Ga)(S,Se)$_2$ alloy system

Author: M. TURCU
In collaboration with: I. M. Kötschau, O. Pakma [1], H. W. Schock, U. Rau

Cu-chalcopyrites such as Cu(In,Ga)Se$_2$ provide the absorber material for the to date most efficient thin-film solar cells. Using the complete alloy system Cu(In$_{1-x}$Ga$_x$)(Se$_{1-y}$S$_y$)$_2$ instead of the standard material Cu(In$_{1-x}$Ga$_x$)Se$_2$ with a moderate Ga-content of $x \approx 0.2$ is interesting when aiming at high open circuit voltage solar cells because the band gap energy E_g of CuInSe$_2$ increases upon alloying with Ga and/or S.

This study investigates electronically active defects in chalcopyrite alloys by admittance spectroscopy of ZnO/CdS/Cu(In$_{1-x}$Ga$_x$)(Se$_{1-y}$S$_y$)$_2$ heterojunctions. By analyzing a large number of Cu(In$_{1-x}$Ga$_x$)(Se$_{1-y}$S$_y$)$_2$ compounds with variations of the Ga/(Ga+In)- and of the S/(S+Se)-ratio, we find a remarkably different trend of deep defect energies if one alloys CuInSe$_2$ with S when compared to alloying with Ga [1]. As shown in Fig. 1, the defect energy of the dominant acceptor state in the CuIn(Se,S)$_2$ system increases with increasing S-content, whereas the energy of the same acceptor remains unchanged over the whole composition range upon alloying CuInSe$_2$ with Ga (Fig. 2).

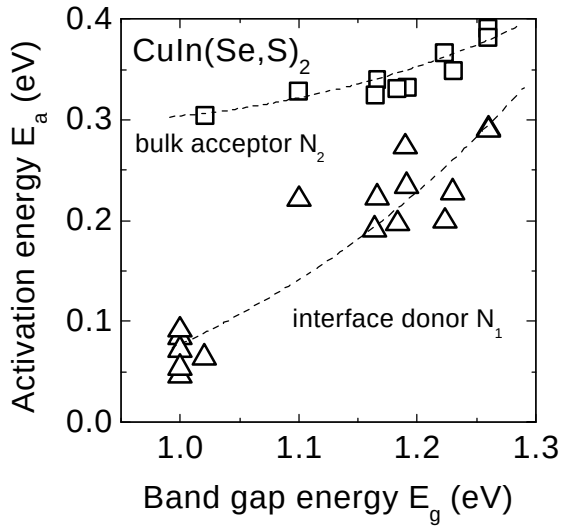

Figure 1: The activation energies of the interface donor N_1 and the bulk acceptor N_2 increase with increasing band gap energy, if CuInSe$_2$ is alloyed with S. Dashed lines are guides to the eyes.

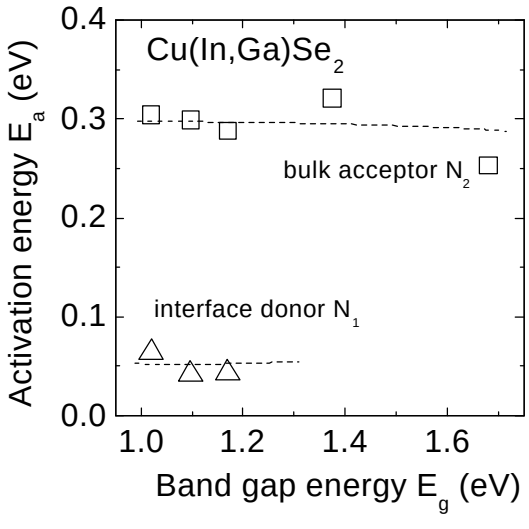

Figure 2: The activation energies of N_1 and N_2 remain constant, if the band gap of CuInSe$_2$ is increased by alloying with Ga.

[1] *Faculty of Arts and Science, University of Mugla, Turkey*

A possible explanation for the different behavior of S and Ga-alloying of $CuInSe_2$ is provided by the fact that alloying $CuInSe_2$ with S decreases the energy E_V of the valence band edge of the alloy whereas alloying with Ga does not [2]. Therefore, we use the acceptor state N2 as a reference energy to determine the internal band offsets within the $CuIn(Se,S)_2$ and the $Cu(In,Ga)Se_2$ system [1]. By analyzing the available data we extrapolate valence band offsets $\Delta E_V \approx 233$ meV and $\Delta E_V \approx -36$ meV for the $CuInSe_2/CuInS_2$ and the $CuInSe_2/CuGaSe_2$ system, respectively. These results agree well with the predictions from theoretical first-principle calculations which yield $\Delta E_V = 280$ meV for $CuInSe_2/CuInS_2$ and $\Delta E_V = 50$ meV for $CuInSe_2/CuGaSe_2$ [2].

It is important to notice that the activation energy of the interface donor N1 in Figs. 1 and 2 also increases upon alloying $CuInSe_2$ with S but remains constant upon alloying with Ga. This observation implies that the Fermi-level position at the $Cu(In_{1-x}Ga_x)(Se_{1-y}S_y)_2$/CdS interface of the heterojunction remains pinned close to the conduction band, thus minimizing interface recombination for the case of $Cu(In,Ga)Se_2$ alloys. In contrast, the increase of the activation energy at the $CuIn(Se,S)_2$/CdS interface with increasing S-content implies that these devices become more sensitive to interface recombination if the absorber band gap increases.

References:

[1] M. TURCU, I. M. KÖTSCHAU, AND U. RAU, Appl. Phys. A **73**, 769 (2001).

[2] S.-H. WEI AND A. ZUNGER, J. Appl. Phys. **78**, 3846 (1995).

4.4 Impedance of dye sensitized TiO_2 solar cells with electrolyte or solid state hole conductor

Author: G. KRON
In collaboration with: G. Nelles [1], A. Yasuda [1], U. Rau, J. H. Werner

Dye sensitized solar cells (DSSC) based on nanocrystalline TiO_2 [1], with power conversion efficiencies above 10 %, have attracted considerable scientific and technological interest. The main disadvantage of these devices lies in the use of the liquid I^-/I_3^- electrolyte. In order to avoid this problem, we follow an attempt of Bach et al. [2] and prepare solid state DSSC using the organic hole conductor MEO-Spiro-TAD instead of an electrolyte. However, the power conversion efficiency of this new type of solar cell is only around 1 %, i.e., much lower than that of the original device that uses a liquid electrolyte.

Here we use impedance analysis to investigate the properties of the solid state solar cell in comparison to the electrolyte DSSC. In case of the electrolyte device, the impedance data are fitted by two *CPE* (constant phase elements), each in parallel with a conductance *G* [3]. Figure 1 shows the exponential increase of the low-frequency capacitance C_{lf} and the low-frequency conductance G_{lf} corresponding to the CPE/G-element with the larger time constants. An exponential increase of C_{lf} is indicative for an injection/diffusion-process of charge carriers in a field-free region similar to the diffusion capacitance of minority carriers in pn-junction diodes [4]. Only at bias voltages V > 1V, i.e., voltages exceeding the open circuit voltage $V_{oc} \approx 0.75$ V, the capacitance saturates at the Helmholtz capacitance of the TiO_2/electrolyte interface. By integrating C_{lf} over *V*, the injected charge carrier density n_{inj} is determined to be approximately 10^{18} cm^{-3} at $V = V_{oc} \approx 0.75$ V [3]. From the fact that saturation of the capacitance increase is found only at higher voltages, we conclude a density of charges in the electrolyte far above 10^{19} cm^{-3}.

The behavior of the solid state DSSC is completely different from the one of the electrolyte DSSC. For forward bias voltages above 0.3 V we find *negative capacitances* (i.e. inductances) as shown in Figure 2. Again, this finding is interpreted in analogy to an all solid-state pn-diode. When approaching high-injection conditions, the number of minority carriers equals or exceeds the net number of doping atoms in the base region of

[1] *Sony International (Europe) GmbH, MSL, Stuttgart, Germany*

a pn-diode. Under these conditions, the number of majority carriers is modulated by the injected minority carriers [5]. In our case, the time delay between electron injection into the TiO_2 and the modulation of the hole concentration in the surrounding hole conductor yields the inductive behavior. From the inductance we conclude that the effective hole concentration in the hole conductor is as low as 10^{17} cm^{-3} [3]. Compared to the density of elementary charges of more than 10^{19} cm^{-3} in the electrolyte, the hole concentration in the hole conductor seems to be too low to warrant charge neutrality around the TiO_2 nanoparticle as it would be needed for proper working conditions of the solar cell. Thus, we identified one major obstacle which has to be overcome in order to improve the power conversion efficiency of the solid-state DSSC.

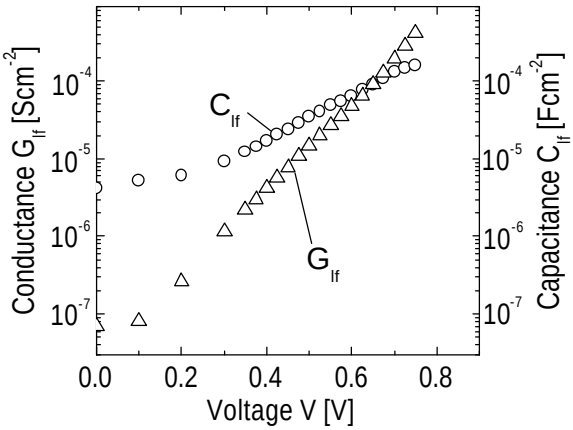

Figure 1: The exponential increase of the low-frequency capacitance C_{lf} and of the conductance G_{lf} is explained by the injection and diffusion of electrons in the TiO_2.

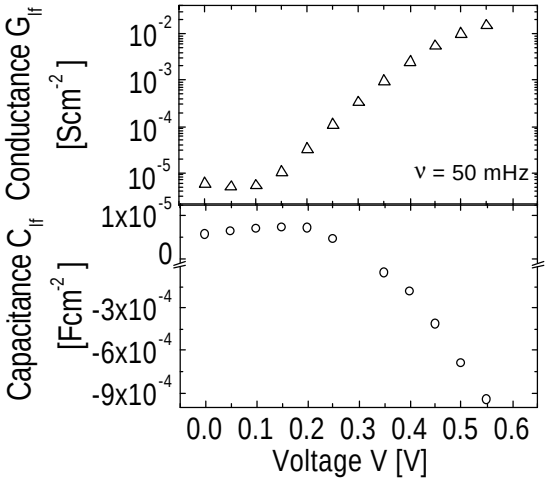

Figure 2: The low-frequence conductance G_{lf} of the solid-state DSSC increases exponentially under forward bias V whereas C_{lf} becomes negative for voltages V > 0.3 V.

References:

[1] B. O'REGAN AND M. GRAETZEL, Nature **353**, 737 (1991).

[2] U. BACH, D. LUPO, P. COMTE, J. E. MOSER, F. WEISSÖRTEL, J. SALBECK, H. SPREITZER, AND M. GRÄTZEL, Nature **359**, 583 (1998).

[3] G. KRON, T. EGERTER, G. NELLES, A. YASUDA, J. H. WERNER, AND U. RAU, Thin Solid Films, in print.

[4] S. M. SZE, *Physics of Semiconductor Devices*, 2nd edition (J. Wiley & Sons, New York, 1986) p. 94.

[5] T. MISAWA, J. Phys. Soc. Japan **12**, 882 (1959).

4.5 Influence of different interfaces on the electrical properties of Cu(In,Ga)Se_2 based heterojunctions

Author: Q. NGUYEN
In collaboration with U. Rau, K. Orgassa, M. Mamor, H. W. Schock

Recent attempts to replace the standard 50 nm CdS buffer layer in solar cells based on Cu(In,Ga)Se_2 (CIGS) by alternative Cd-free buffers like Zn(OH,S) and $In_x(OH,S)_y$ were quite successful [1, 2]. However, the efficiencies of devices with these alternative buffer layers still lack behind the efficiencies of standard CdS-devices. Moreover, the origin of metastabilities in devices with chemical bath deposited alternative buffer layers, i.e., light or voltage bias-induced changes of the electronic device properties, is still an open question. Devices with $In_x(OH,S)_y$ buffer exhibit an electrical metastability that causes a hysteresis in the current (I)-voltage (V) characteristics. The shape, and consequently the fill factor, of an illuminated I/V curve depends on whether the characteristics is measured from negative voltages bias towards positive ones or vice versa.

In order to elucidate the question whether the hysteresis in I/V curves of $In_x(OH,S)_y$ buffer devices depends on the properties of the $In_x(OH,S)_y$ buffer, the interface between CIGS/$In_x(OH,S)_y$ or that between $In_x(OH,S)_y$/i-ZnO, we investigate and compare the electrical properties of devices with different buffer layer combinations:

(i) Reference 1: CIGS/CdS/i-ZnO

(ii) Reference 2: CIGS/$In_x(OH,S)_y$/i-ZnO

(iii) Type A: CIGS/CdS/$In_x(OH,S)_y$/i-ZnO

(iv) Type B: CIGS/$In_x(OH,S)_y$/CdS/i-ZnO.

The I/V curves of the illuminated samples are shown in Fig. 1.

There is no evidence for a hysteresis loop in the illuminated I/V curves in case of reference 1 samples, consequently, the interfaces CIGS/CdS and CdS/ZnO are not related to this phenomenon. If a CdS layer separates the interfaces CIGS/$In_x(OH,S)_y$ and $In_x(OH,S)_y$/ZnO in type A and type B devices, respectively, a current-voltage (I/V) hysteresis in these devices could be assigned to the interface $In_x(OH,S)_y$/ZnO and/or CIGS/$In_x(OH,S)_y$.

It is interesting to note that the I/V hysteresis is observed not only in the sample reference 2 but also in devices of type A with an $In_x(OH,S)_y$/

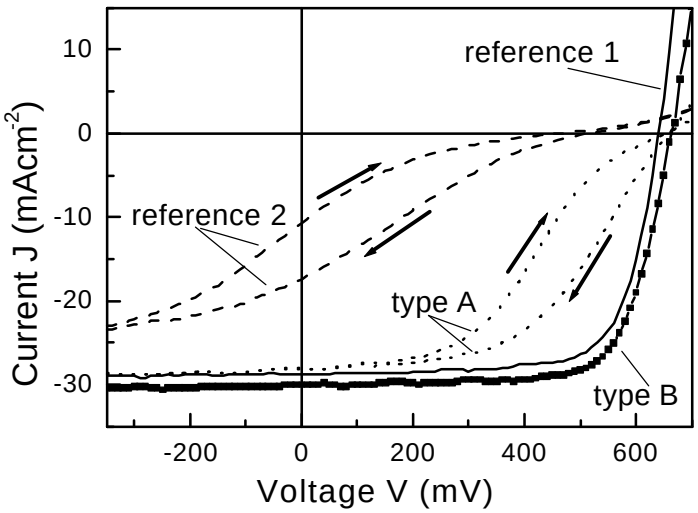

Figure 1: Current-voltage characteristics of illuminated samples. The arrows show the direction of applied voltage bias for the devices that exhibit the IV hysteresis (reference 2 and type A). The IV curves of CdS and type B devices have almost the same values in both directions of measurement.

i-ZnO interface, where the CIGS surface is even separated from the $In_x(OH,S)_y$ by a CdS layer with 50 nm thickness [3]. The device with a CdS buffer as well as device type B, where the $In_x(OH,S)_y$ layer is separated from the i-ZnO by a very thin (20nm) CdS layer, do not exhibit the I/V hysteresis, i.e. the cell parameters are almost the same in both modes of measurement [3]. These results imply that the I/V hysteresis in the device CIGS/$In_x(OH,S)$/ i-ZnO is directly related to the $In_x(OH,S)_y$/ i-ZnO interface but not to the CIGS/$In_x(OH,S)_y$ interface or to the bulk properties of the $In_x(OH,S)_y$ buffer. Moreover, devices of type B, where the interface CIGS/CdS is separated by the $In_x(OH,S)_y$, have higher efficiencies (14.5%) than devices with the CdS buffer layer (13.2%). This result is in contrast to the suggestion in Ref. [4], where the beneficial role of the CdS buffer for the device properties is explained by the formation of a homojunction by Cd-diffusion into the bulk of the CIGS film. We suggest that CdS controls the interface to the ZnO window. Thus, the development of alternative non-CdS buffer layer has to focus on the interface to the ZnO window layer.

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4.6 Optical losses in ZnO/CdS-window layers for Cu(In,Ga)Se$_2$ thin film solar cells

Author: K. ORGASSA
In collaboration with: Q. Nguyen, U. Rau, H. W. Schock, J. H. Werner

The use of a CdS buffer layer is a prerequisite for a reproducible and efficient heterojunction in ZnO / CdS / Cu(In,Ga)Se_2 (CIGS) solar cells [1]. However, many efforts concentrate on the replacement of this layer by other materials [2] or even its entire omission [3]. Besides environmental concerns, a main reason for these efforts is the hope for an increased short circuit current density of devices without the CdS buffer, since this layer reduces the blue response of the quantum efficiency. We investigate the correlation between the short circuit current density J_{sc} and the CdS layer thickness d_{CdS} in CIGS solar cells. In contrast to the expected increase of J_{sc} for very thin CdS layers, we observe an almost constant behaviour of $J_{sc}(d_{CdS})$ for CdS thicknesses below $d_{CdS} \approx 40$ nm.

Integrating a CdS layer into the system ZnO / CIGS affects J_{sc} in two ways. First, the CdS layer deteriorates the internal quantum efficiency at energies above the CdS bandgap ($E_{g,CdS} \approx 2.4$ eV). This deterioration originates from a low collection efficiency of charge carriers photo-generated in the CdS buffer and leads to a decrease of the current density, that we call the *electronic loss* ΔJ_{sc}^{el}. However, this loss is compensated by a reduced spectral reflection of the solar cell, that increases J_{sc}. The refractive index of CdS ($n_r \approx 2.4$) lies in between the refractive indices of ZnO ($n_r \approx 1.9$) and CIGS ($n_r \approx 2.9$). The CdS therefore devides the large step between the refractive indices of ZnO and CIGS into two smaller steps. The reduced reflection resulting from the better match of the refractive indices leads to an increase of the short circuit current density, i.e. to an the *optical gain* ΔJ_{sc}^{opt}. The total change ΔJ_{sc} of the short circuit current density of the solar cell is given by the sum $\Delta J_{sc}^{opt} + \Delta J_{sc}^{el}$, as both effects appear at the same time.

Base-line CIGS solar cells are fabricated with CdS layer thicknesses between d_{CdS} = 0...85 nm. Figure 1 shows the optical gain ΔJ_{sc}^{opt}, the electronic loss ΔJ_{sc}^{el}, and the total current density change ΔJ_{sc} for the devices as a function of d_{CdS}. The optical gain is evaluated from integral reflection spectra, and the electronic loss from quantum efficiency measurements [4]. We note that both effects are of the same order of magnitude within the investigated range of CdS thicknesses. As the

most important consequence, optical gain and electronic loss almost compensate each other up to a thickness of $d_{CdS} \approx 40$ nm. Thus, an optimization of the short circuit current density is not achieved by simply omitting the CdS layer, but rather by replacing the CdS by an alternative buffer material with higher bandgap energy and optical constants similar to those of CdS.

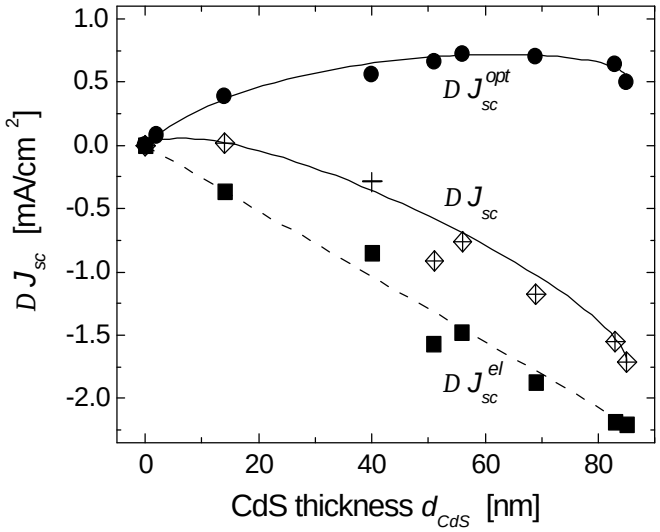

Figure1: Optical gain ΔJ_{sc}^{opt} (circles), electronic loss DJ_{sc}^{el} (squares), and the total current density change DJ_{sc} (crossed diamonds) The upper two datasets are connected with spline curves as guides to the eye, the electronic loss follows a linear fit. Optical gain and electronic loss almost compensate each other for CdS thicknesses between d_{CdS} » 0 and 40 nm.

We proceed with a similar analysis for the dependence of the short circuit current density on the thickness of the ZnO layer in order to derive optimized thicknesses for the CdS / ZnO window layer system [4]. The reflection of the layer system is minimal at a CdS thickness of d_{CdS} = 50 nm, a ZnO thickness of d_{ZnO} = 50 nm or 350 nm, and a MgF_2 antireflection coating of d_{MgF2} = 100 nm. We fabricate a CIGS thin film solar cell with optimized reflection properties. The remaining reflection of the layer system (without grid) causes a loss in short circuit current density of less than 1.7 %. The total area efficiency of the solar cell is 17.8 %, in spite of a grid shading of more than 6 %.

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[4] K. ORGASSA, Q. NGUYEN, I. M. KÖTSCHAU, U. RAU, H. W. SCHOCK, AND J. H. WERNER, in *Proc.17th Europ. Photovolt. Solar Energy Conf.*, in print.

4.7 Numerical Modeling of Pulsed Laser Crystallization of Thin-Film Silicon

Author: J. R. KÖHLER
In collaboration with: R. Dassow, J. H. Werner

We investigate the crystallization behavior of amorphous silicon films on glass by using pulsed lasers with very high repetition rates up to 100 kHz. Our experimental results indicate a strong dependence of the grain width *g* on film thickness *d* as well as on the repetition rate *f* of the laser [1]. The grain width rises from g = 0.27 µm to g = 3.59 µm if the film thickness increases from d = 50 nm to d = 300 nm and the repetition rate *f* from f = 20 kHz to 100 kHz. We use a purpose-developed two-dimensional finite difference numerical model [2, 3] to calculate the evolution of the temperature in the silicon film and in the glass substrate. The temperature increase extracted from numerical results is displayed in Fig. 1. The temperature increase from the first laser shot to the second one is significantly lower than the final temperature, which is reached after a few thousand laser shots. The temperature increase reaches up to 500 K and can be further increased as soon as lasers with higher repetition rates will be available. An increase of both, the film thickness *d* and the repetition rate *f*, decrease the solidification velocity *v* of the film. A comparison of the solidification velocity v_s and the

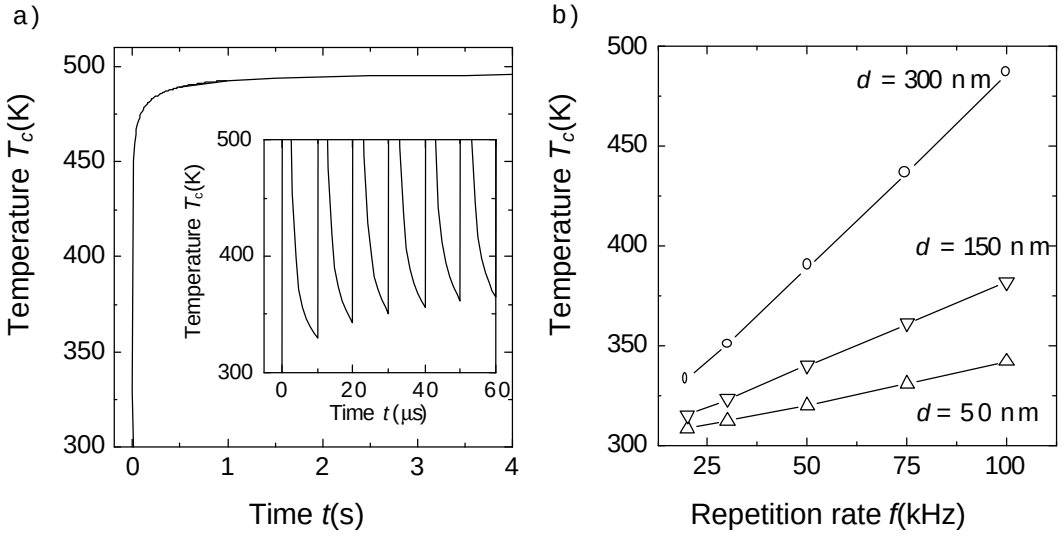

Figure 1: a) Surface temperature T_c of a 300 nm thick silicon film versus time. During the first laser pulses T_c increases very rapidly and begins to saturate after approx. 0.5 s. Inset graph displays the temperature evolution during the first six laser pulses. b) Saturated surface temperature of silicon films with different thicknesses in dependence of the repetition rate of the laser.

measured grain width *g* shows a linear correlation. Figure 2 proves this finding, which holds for a wide variety of Si-film thicknesses, pulse repetition rates of the laser pulses, and substrate materials.

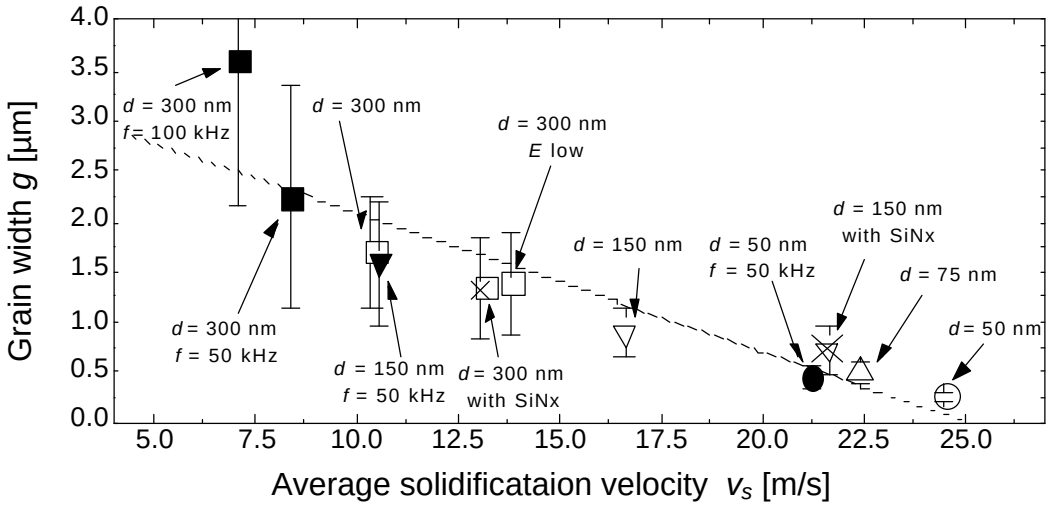

Figure 2: Solidification velocity v_s *is extracted from numerical simulations. Data points without a stated f-value hold for f = 20 kHz. Error bars indicate the standard deviation of the grain width distribution. The dotted line is a linear fit to the data points.*

Numerical simulations in combination with experimental results lead us to the conclusion, that both, the heat transport from the film to the substrate as well as the heat transport in the Si-layer, govern the crystallization behavior and hence the material properties of laser-crystallized polycrystalline Si-films. In particular, laser crystallization with pulse repetition rates *f* of up to *f* = 100 kHz using the sequential lateral solidification process significantly improves the material quality, i.e. the grain size of the films. This behavior originates from the fact, that the silicon film and substrate still "remember" previous laser pulses, which preheat the substrate.

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4.8 Ion Bombardment Enhances Low Temperature Silicon Epitaxy

Author: T. A. WAGNER
In collaboration with: L. Oberbeck, R. B. Bergmann

The formation of abrupt junctions in microelectronic devices or the fabrication of solar cells on foreign substrates often require a low-temperature epitaxy step during processing. Molecular beam epitaxy can provide high-quality epitaxial films, however, at low deposition temperatures (~500°C) epitaxial growth is hampered by low adatom mobility, resulting in point defects and defect clusters in the films.

We use ion-assisted deposition (IAD), an advanced molecular beam epitaxy method that provides additional energy for film growth at low temperatures by the use of accelerated Si^+-ions in the Si beam. In IAD, a small fraction (~ 1%) of evaporated silicon atoms are ionized by a toroidal-shaped ionizer that is located between the silicon evaporator and the substrate. The energy of the Si^+ ions is controlled in the range from 0 to 1250 eV by applying an acceleration voltage to the substrate. For device fabrication, films are in-situ doped by co-evaporation of either boron or phosphorous atoms.

Ion bombardment is able to improve the structural properties of films deposited at low temperatures by transfer of ionization and kinetic energy of the Si^+-ion to the surface atoms, but may also cause additional defects such as interstitials and vacancies by the displacement of Si-atoms in the uppermost Si monolayers. In order to optimize the film quality we use an optimum ion energy of 20 eV. Higher energies result in increased point defect densities and lower minority carrier diffusion lengths of the films.

Epitaxial growth by IAD is highly dependent on the substrate orientation. Figure 1 demonstrates the benefits of hyperthermal Si ions in the case of (100)-oriented epitaxial silicon films: The minority carrier diffusion length L of films deposited at T_{dep} = 650°C increases with applied acceleration voltage [1]. However, in the case of (111)-, (113)- and (110)-oriented films the minority carrier diffusion length decreases upon applying an acceleration voltage to the substrate. Independent of the deposition temperature, the density of extended defects n_{ep}, i.e. stacking faults and dislocations, in (100)-oriented films is below 1×10^3 cm^{-2}, while we find high values of $n_{ep} > 1 \times 10^5$ cm^{-2} in epitaxial films deposited on (111)-oriented substrates. Therefore, IAD allows for high-

quality low temperature epitaxy of (100)-oriented films, but is less suited for deposition on non-(100)-oriented or polycrystalline substrates without preferred (100)-orientation.

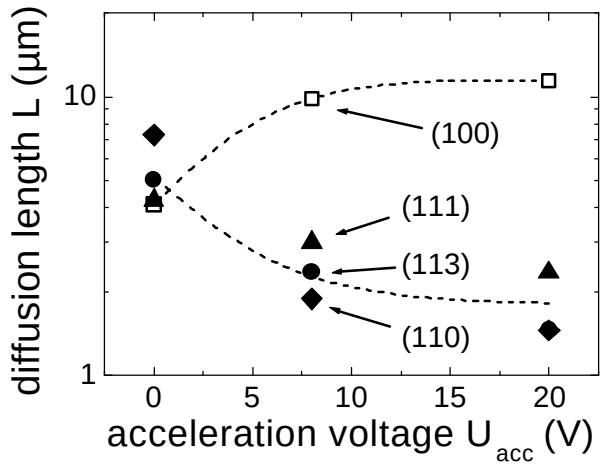

Figure 1: Influence of ion energy on the minority carrier diffusion length L of films deposited at T_{dep} = 650°C. In the case of (100)-oriented films an increase of the acceleration voltage from 0 V to 8 V results in an increase of L by more than a factor of two. However, for non-(100)-oriented films the minority carrier diffusion length decreases with rising ion energy.

For example, a 20 µm-thin epitaxial solar cell with emitter and base layer deposited at T_{dep} = 650°C and a high deposition rate of r_{dep} = 0.8 µm/min on a (100)-oriented Si-wafer shows an open circuit voltage V_{OC} = 622 mV and an efficiency h = 12.7% without any light trapping structures [2].

The influence of the silicon ions on the structural and electronic properties of films deposited at lower temperatures (T_{dep} < 500°C) is currently under investigation.

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4.9 Monocrystalline Thin-Film Silicon By Layer Transfer

Author: C. BERGE
In collaboration with: R. B. Bergmann, T. J. Rinke, T. A. Wagner, J. H. Werner

During the last three years, we have studied a process that allows the transfer of epitaxially deposited (mono-) crystalline silicon thin films of high electronic quality from a host wafer onto a foreign substrate [1]. Using this approach eliminates the need for wafer thinning for applications that require thin monocrystalline silicon on foreign substrates, and enables also multiple processes using a single silicon wafer.

The epitaxial film is grown on top of a monocrystalline silicon wafer which was treated to allow the consecutive separation of the film. The treatment of the wafer is rather simple: The wafer is anodically etched in an HF-containing solution. The etching is carried out in a two-step-process with an etching current switching from low to high current density. This process leads to a layer structure with a low-porosity layer of several 100 nm thickness on top of a thin buried layer of high porosity. When the wafer is heated to high temperatures around 1100 °C, both porous layers recrystallize, leading to a monocrystalline layer on top containing large voids, which we refer to as *quasi-monocrystalline silicon* (QMS). The buried layer with high porosity, instead, forms a layer with only small amounts of silicon. This layer is mechanically weak and allows the detachment of the QMS layer from the original wafer. During recrystallization the pores of the QMS film close completely near the surface. Therefore, one obtains an undisturbed surface which allows for high-quality epitaxial growth. Figure 1 shows a cross section scanning electron microscopy image of the layer structure after restructurization of the porous double layer and epitaxial growth on top.

The QMS technique enables one to repeatedly use a Si wafer for epitaxy. While still attached to the host wafer, the layer undergoes processing steps including wet etching as well as high temperature processing. After device fabrication, the layer is detached from the wafer and transferred to a substrate suitable for a desired application.

In the last year, we successfully demonstrated the transfer of epitaxial films on top of QMS films to plastic foils [2]. Figure 2 shows a photo of such a transferred film. The films are flexible even though they have a monocrystalline structure.

In the field of photovoltaics, the technology offers the possibility of using standard pn-junction silicon solar cell technology with high process temperatures while at the end of the process obtaining thin-film solar cells. The *ipe* currently holds the world record for transferred monocrystalline silicon thin-film solar cells with an independently confirmed efficiency of 16.6 % [3].

The possibility of reusing an individual silicon wafer several times as a host wafer for the epitaxial deposition and the following formation of the solar cell, opens the way for cost-effective thin-film technology while preserving the high material quality of monocrystalline silicon.

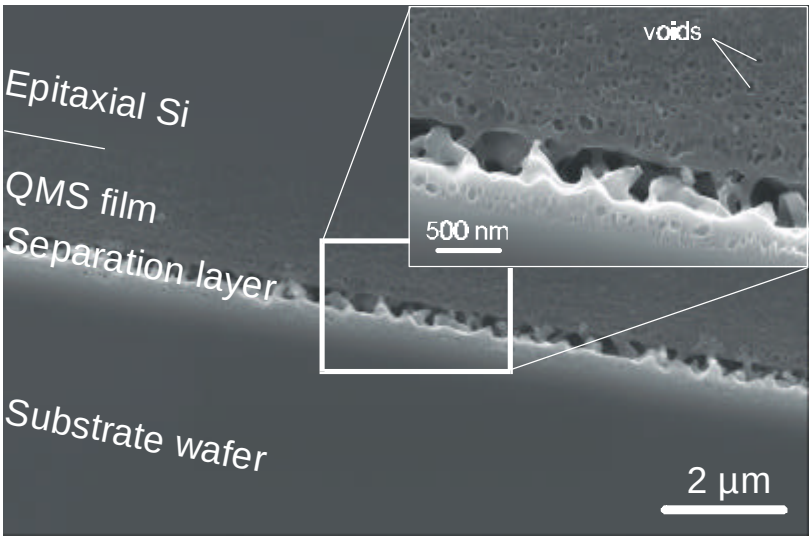

Figure 1: Cross section scanning electron microscopy picture of the double-layer porous structure after restructurization. The small picture shows a detail of the separation layer and the QMS film.

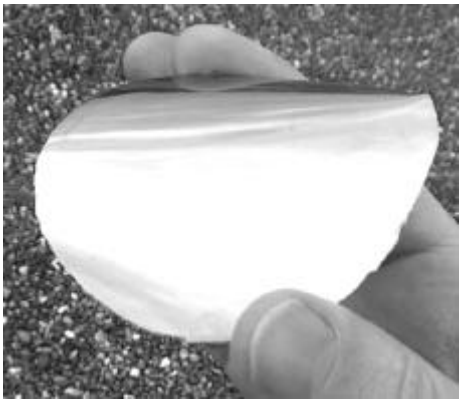

Figure 2: Photograph of a 14 µm thick epitaxial silicon film on top of a 1.5 µm thick QMS film, transferred to a plastic foil.

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4.10 Integrated Photovoltaics: PV on clothes

Author: C. E. M. GEMMER
In collaboration with: B. Zinßer, J. Krämer, S. Reinold, R. J. Kaiser, M. B. Schubert, U. Sanzenbacher,[1] J. H. Werner

In recent years, the use of mobile electronic devices such as cellular phones, personal digital assistants (PDAs), MP3 players, radios, world receivers has spread widely. Usually, the power supply is based on accumulators, charged up on standard power sockets. To provide a high mobility for users of the low-power devices, we propose the integration of solar cells onto clothing, that serve as energy supply for the accumulator charging. A huge demand exists on integrated photovoltaics on and in clothing that is not satisfied yet. For that purpose, we design a solar hat and a solar jacket, called *Jack I*, using commercial solar cells based on monocrystalline silicon (c-Si) in close cooperation with the "Staatliche Modeschule Stuttgart".

The cell array of the solar hat shown in Fig. 1a covers the direct energy supply of a world receiver under indoor illumination intensity of 10^{-3} to 10^{-2} suns. *Jack I* (Fig. 1b) features a rechargeable battery including a charge controller to bridge the times of darkness and provides energy for the active indoor use of a minidisk player as well as of a cellular phone. In order to achieve the required high output voltages at low illumination, we construct the prototype of the hat with 4 parallel-connected strings each built up of 6 series-connected solar cells. The cell array of *Jack I* consists of 8 modules each with 9 series-connected c-Si pn-junctions. Ordinary Schottky diodes electrically decouple the cell strings. The processing of our quasi-flexible cell modules proceeds with sawing and contacting of the single cells each covering an area of $A = 8.1\ \mathrm{cm}^2$. Laminating the modules into a thin transparent plastic film leads to mechanically stable, completely series-connected quasi-flexible cell strings. Subsequently, we sew the strings on the brim of the hat and on the shoulder area of the solar jacket. The complete modules yield an open circuit voltage of $V_{oc} = 3.0$ V for the hat and $V_{oc} = 4.8$ V for *Jack I* under illumination of 0.5 suns. The laminated cell array integrated in *Jack I* exhibits an efficiency of $h = 11.0$ %. The complete solar jacket generates powers up to $P = 5.5$ W under the intensity of 1 sun. Figure 1 demonstrates the successful construction of the solar hat (Fig. 1a) and

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Figure 1: The figures demonstrate the successful construction of the solar hat (figure 1a) and jacket called Jack I (figure 1b) and emphasize the fact, that the integration of photovoltaics onto clothing meets modern fashion design. Monocrystalline silicon is the base material of the solar cells that supply energetically mobile communication electronics such as cellular phones, personal digital assistants (PDAs), MP3 players, radios and world receivers.

Jack I (Fig. 1b) and emphasizes the fact, that the integration of photovoltaics onto clothing meets modern fashion design.

The next design will integrate *flexible* solar cells deposited on plastic foils onto clothing to make the wearing of solar clothing more comfortable. Besides, these solar jackets provide enough energy for an active usage of a PDA with a color display.

5. Verzeichnis der Publikationen/ *List of Publications*

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6 Promotionen 2001 / *Ph. D. Theses 2001*

DASSOW, RALF	Laserkristallisation von Silicium
MAGORIAN FRIEDLMEIER, THERESA	Multinary Compounds and Alloys for Thin-film Solar Cells
OBERBECK, LARS	Ionenassistierte Deposition von Siliciumschichten

7 Diplomarbeiten 2001 / *Diploma Theses 2001*

BUCK, THOMAS	Herstellung von Niedertemperatur-Epitaxieschichten für die Mikroelektronik
DEMIR, JAKOB	Charakterisierung von Dünnschichttransistoren
ELLENRIEDER, MARC	3-D-Bewegungsprädiktion von Objekten und deren Einfluß auf die „Pose Estimation“
KÄMPCHEN, NICO	Modellbasierte „Pose Estimation“ von Objekten in Stereo-Bildsequenzen
NEMTANU, CRISTIAN	Autonome Bildaufnahme- und Übertragungsstation
SCHÄFER, KLAUS	Entwicklung und Implementierung einer Bildanalyse-Software in JAVA
SCHLENKER, MARKUS	Meßdatenerfassung für Erprobungsträger für hochfliegende Plattformen
TIPPMANN, HOLGER	Implementierung und Installation eines XML-Datenbankservers

8 Studienarbeiten 2001 / *Student Works 2001*

BRENDLE, WILLI	Herstellung und Charakterisierung von Dünnschichtsolarzellen auf der Basis transferierter, monokristalliner Siliciumschichten
GÖTTLING, SILKE	Entwurf von Operationsverstärkern auf der Basis des IMS Mixed Signal Gate Array
LIAW, CORVIN	Fensterschichten für $Cu(In,Ga)(Se,S)_2$ Dünnschichtsolarzellen
MATTEIS, JULIAN	The Selenium Flux During the Coevaporation Process of $Cu(In,Ga)Se_2$ Thin Films for Solar Cells
OCKER, FRANK	Entwicklung eines Maskensatzes zur Herstellung eines Minimoduls
SPEER, TIM	Scheckkarten-Energieversorgung mit Dünnschichtsolarzellen aus kristallinem Silicium

9 *ipe* Kolloquium 2001

15. 1. KLAUS EBERHARDT, M+W Zander Stuttgart, *"Aktuelle Entwicklungen in der Halbleitertechnologie und künftige Halbleiterfabriken"*

22.1 RALF ZEDTLITZ, Infineon, Dresden, *"Dünne Schichten auf 300 mm Wafern"*

29.1 CELINE TRENNEN, Université de Caen, *"A new approach to the fabrication of Si/SiO_2 superlattices using reactive magnetron sputtering"*

5.2 FRANCESCA FERRAZZA, Eurosolare (AGIP, ENI S.p.A), *"Research and Development for Silicon Cell Manufacturing"*

12.2. NORBERT WILLNECKER, *K*eithley Instruments, *"Messung kleinster Ströme und Spannungen"*

7.5 S. GÄRTNER, Technologie-Lizenz-Büro (TLB) der Bad.-Württ. Hochsch. GmbH, *"Schutz und Verwertung von Erfindungen"*

14.5 CHRISTOPH. BRABEC, Universität Linz, *"Organische Solarzellen"*

21.5 REINER KLENK, Hahn Meitner Institut (HMI), Berlin, *"Stand der $CuInS_2$ Solarzellenentwicklung"*

28.5 JÖRG WRACHTRUP, 3. Phys. Inst. Universität Stuttgart, *"Photovoltaik in makromolekularen Systemen"*

11.6 GERD LIPPOLD, Solarion GmbH, Leipzig, *"Ionenstrahltechniken zur Herstellung von $CuInSe_2$ Dünnschichtsolarzellen"*

18.6 FERDINAND SCHOLZ, 4. Phys. Inst. Universität Stuttgart, *"Neue Entwicklungen für blaue Laser und Leuchtdioden"*

2.7 REINER MAUCH, Schott Displayglas GmbH, Mainz *Flachdisplays: Markt und Technologien*

9.7. HANS JÖRG GABLER, Zentrum für Sonnenenergie- und Wasserstoff-Forschung, *"Erträge von netzgekoppelten PV-Anlagen"*

29.10 DIETER BRAUNGER, *"Patente wozu? - die Rolle des Patentanwalts"*

5.11 RALF WEHRSPOHN, Max-Planck-Inst. of Microstructure Physics, Halle (Saale)
"Photonische Kristalle"

12.11 MARTIN PFEIFFER, Institut für Angewandte Photophysik, Technische Universität Dresden, *"Organische Halbleiter: Grundlagen und Anwendung in Leuchtdioden und Solarzellen"*

19.11 BRANKO PIVAC, Materials Physics Dept. Rudjer Boskovic Inst., Zagreb, Croatia, *"Oxygen in Silicon"*

26.11 ANDREAS HINSCH, Freiburger Materialforschungszentrum, Freiburg, *"Farbstoffsolarzellen; Stand der Dinge und zukünftige Entwicklungen"*

3.12. HERMANN STOLL, Max Planck Institut für Metallforschung, Stuttgart, *"Rauschen in Metallschichten"*

10.12 MARC BURGELMAN, University of Gent, Electronics and Information Systems, Gent, Belgium, *"Simulation of Heterojunction Transport by Numerical Models"*

10 Gäste und Stipendiaten 2001 / *Guests 2001*

BALBOUL, MOHAMMED, National Center for Radiation, Nasr-City, Cairo, Egypt, 1.10.1999 – 30.9.2001

CAO, XINMIN , Research Center for Electric Light Sources, Southeast University, Nanjing, VR China, 1.10.1999 – 30.9.2002

CHEGAAR, MOHAMMED, Ferhat Abbas University, Setif, Algeria, 20.6. – 21.7.01

CHERNYK, OLENA, Kharkov State Polytechnical University, Kharkov, Ukraine, 1.7. – 31.12.01

EMELIANOV, VITALI, Technological Centre, Moscow Institute of Electronic Technology, Moscow, Russia, 1.4.2000 – 31.12.2001

KOVTUN, NAZAR, Kharkov State Polytechnical University, Kharkov, Ukraine, 1.7. – 31.12.01

NGUYEN HONG QUANG, National Center for Natural Science and Technology, Hanoi, Vietnam, 1.10.1999 – 30.9.2002

PAKMA, OSMAN, Mugla University, Mugla, Turkey, 1.5. – 31.8.01

TARETTO-ZEYEN, Kurt, Universidad Nacional del Comahue, Buenos Aires, Neuquén, Argentina, 1.1.1999 – 31.12.2001

TURCU, MIRCEA , National Institute for Research and Development in Electrochemistry and Condensed Matters, Timisoara, Romania, 1.4.1999 – 31.12.2001

YAMAMOTO, YUKIO, Fukui National College of Technology, Sabae-shi, Fukui, Japan, 1.5.01 – 28.2.02

11 Wissenschaftliche Geräte und Analysemethoden / *Scientific Instruments and Methods of Analysis*

11.1 Abscheideverfahren / Deposition Methods

Material / *Materials*	***Abscheideverfahren /Deposition method***	**Anwendung / *Application***	**Kontakt / *Contact***
Amorphe Halbleiter / *amorphous semiconductors* (a-Si:H, nc-Si, etc.)	Plasma-CVD (DC, RF, VHF), Niedertemperatur (70^{o}C)/ *low temp. deposition (70^{o}C)* thermokatalytische Depos. *hot-wire-CVD* Legierung / *alloying* (Ge, C) Dotierung / *doping* (B,P,..)	Dünnschicht-Solarzellen und Sensoren / *thin-film solar cells and sensors*	Schubert
Kristallines Silicium / *crystalline silicon* (mono, poly-Si)	CVD, RT-CVD,Plasma-CVD Hot-wire- CVD Ionenassistierte Epitaxie / *Ion Assisted Deposition (IAD)*	Dünnschicht-Solarzellen und Elektronik / *thin-film solar cells and electronics*	Schubert
Kristallines Silicium / *crystalline silicon*	Laserkristallisation / *laser crystallization*	Dünnschicht-transistoren / *thin-film transistors*	Köhler
Poröses Silicium / *porous silicon*	Transferverfahren / *transfer methods*	Elektronik auf Glas und flexiblen Sustraten / *Electronics on glass and flexible substrates*	Schubert
Polykristalline Verbindungs-halbleiter / *compound semiconductors* $Cu(In,Ga)(Se,S)_2$ CdS,ZnS, ZnSe,	Aufdampfung, mit mehreren Quellen und individueller Ratenregelung, Katodenzerstäubung, chemische Badabscheidung / *multi-source evaporation*, *sputtering, chemical bath deposition*	Dünnschicht-Solarzellen / *thin-film solar cells*	Schock
Transparente leitfähige Schichten / *transparent conducting films* ITO, ZnO, SnO_2	Katodenzerstäubung / *sputtering (RF, DC, reactive)*	Solarzellen und Sensoren / *solar cells and sensors*	Schock, Schubert

11.2 Strukturelle Analysenverfahren / Structural Materials Analysis

Methode / ***Method***	**Material /** ***Materials***	**Anwendung /** ***Application***	**Kontakt /** ***Contact***
Photoelektronen-spektroskopie / *photoelectron spectroscopy (small spot XPS/-ESCA, UPS)*	Halbleiter Oberflächen, Dünnschichten / *semiconductor surfaces, thin-films* $CuInSe_2$, ZnO	Solarzellen (in-situ Studien des Wachstums, elektronische Bandstruktur) / *solar cell materials (growth, band structure)*	Bilger
Sekundär-Ionen Massenspektro-metrie / *Secondary Ion Mass Sectroscopy (SIMS)*	Dünne Schichten, Schichtsysteme / *compositional analysis of thin films*	Laterale Elementverteilungen, Tiefenprofile, Spurenelemente / *lateral element distribution, depth profiles, trace elements*	Bilger
Diffraktometrie (streifender Einfall) / *grazing incidence X-ray diffraction*	Silizium-, Verbindungshalbleiter-schichten / *thin film silicon and compound semiconductors*	Phasenanalyse, Textur von dünnen Schichten / *phase analysis,texture of thin films*	Schock
Rasterelektronen-mikroskop (incl. Röntgenanalyse) / *scanning electron microscopy, energy dispersive x-ray analysis*	Mikro- und polykristalline Dünnschichten / *micro- and polycrystalline thin films*	Struktur, chemische Zusammensetzung, Tiefenprofile / *structure, chemical composition, depth profiling*	Schock
Rasterkraft- und Rastertunnelmi-kroskop / *atomic force and scan-ning tunneling microscope*	Oberflächen von mikro- und polykristallinen Dünnschichten / *Surfaces of micro- and polycrystalline thin films*	Elektrische und strukturelle Eigenschaften von Halbleiteroberflächen / *semiconductor surfaces (electronic and structural properties)*	Schock

11.3 Analyse optischer Eigenschaften/ *Analysis of Optical Properties*

Methode / *Method*	**Material**	**Anwendung / *Application***	**Kontakt / *Contact***
FT-IR-Spektroskopie / *FT-IR-spectroscopy*	wasserstoffhaltige, amorphe und mikrokristalline Dünnschichthalbleiter / *hydrogen-containing amorphous and microcristalline thin film semiconductors*	Solarzellen, Sensoren (Wasserstoffgehalt, strukturelle Eigenschaften) / *solar cells, sensors*	Schubert
Raman-Spektroskopie / *Raman-spectroscopy*	amorphe und mikrokristalline dünne Schichten / *amorphous and microcrystalline thin films*	Solarzellen, Sensoren (strukturelle Eigenschaften) / *solar cells, sensors*	Schubert
Photolumineszenz / *photoluminescence*	Silizium, Verbindungs-halbleiter / *silicon, compound semiconductors*	Charakterisierung von Halbleitern / *characterization of semiconductors*	Rau
Photothermische Ablenkungs-Spektroskopie / *photothermal deflection spectroscopy* (PDS) Methode des konst. Photostroms./. *Constant Photocurr. method (CPM)*	dünne Schichten / *thin films*	optische von Absorption Halbleiterschichten / *optical absorption of semiconductor thin films*	Schubert
Transmission, Reflexion / *optical transmission and reflection (UV to NIR, direct, diffuse)*	dünne Schichten für Solarzellen, Sensorik und Optoelektronik / *thin films for solar cells, sensors, and opto-electronics*	Bestimmung von Schichtdicke, Brechungsindex, Extinktionskoeffizient / *film thickness, refractive index, absorption* .	Rau
In-situ Ellipsometrie / *in-situ ellipsometry*	dünne Schichten, Mehrschichtsysteme / *thin films, multi-layer systems*	Schichtwachstum und Grenzflächeneffekte / *film growth*	Schubert

11.4 Analyse elektro-optischer Eigenschaften / *Analysis of Electro-Optical Properties*

Methode / *Method*	**Material / *Materials***	**Anwendung / *Application***	**Kontakt / *Contact***
Stationäre und transiente Photo- und Dunkel-leitfähigkeit / *stationary and transient dark- and photoconductance*	amorphe und polykristalline Dünnschichthalbleiter / *amorphous and polycrystalline thin film semiconductors*	Bestimmung von Trägerdichten, Diffusionslängen, Fermi-Energie / *carrier densities, diffusion lengths, Fermi energy, etc*.	Schubert
Hall Messungen, Time-Of-Flight Spektroskopie, Quantenausbeute, transiente Mikrowellen-absorption / *Hall measurements, Time-Of-Flight (TOF) spectros-copy, quantum efficiency, m-wave absorption*	Halbleitermaterialien und -baulelemente / *semiconductor materials and devices*	Trägerbeweglichkeiten, Diffusionslängen, Minoritätsträger-lebensdauer, elektro-nische Zustandsdichte / *carrier mobilities, diffusion lengths, minority carrier lifetime, densities of states*	Rau
Admittanz-Spektroskopie, DLTS, modulierte Photoströme / *admittance, DLTS, modulated photocurrents*	Dünnschichthalbleiter und –bauelemente / *thin film semiconductors and devices*	Solarzellen, Sensoren (Defekte, elektrische Transporteigenschaften , interne Barrieren) / *solar cells, sensors (defects, electronic transport, internal barriers)*	Rau
IU Kennlinien / *IV characteristics*	Dioden, Solarzellen / *diodes, solar cells*	Transporteigensch. / *transport properties*	Rau
Spektrale Empfindlichkeit, Quantenwirkungs-grad / *Spectral response Quantum-efficiency*	Dioden, Solarzellen / *diodes, solar cells*	Transporteigenschaften optische Eigenschaften / *transport properties optical properties*	Rau

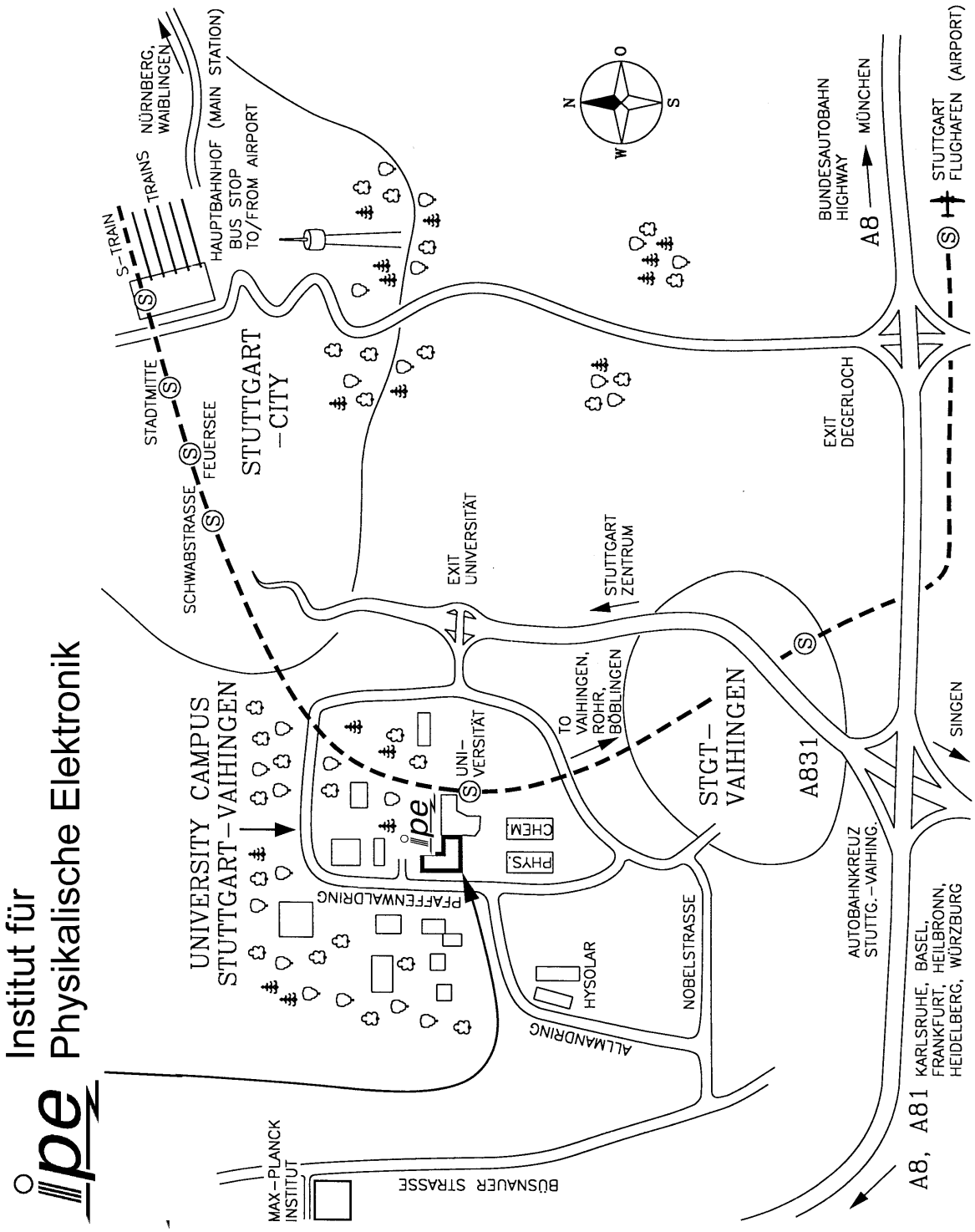
12 Mitarbeiter / *Staff Members*

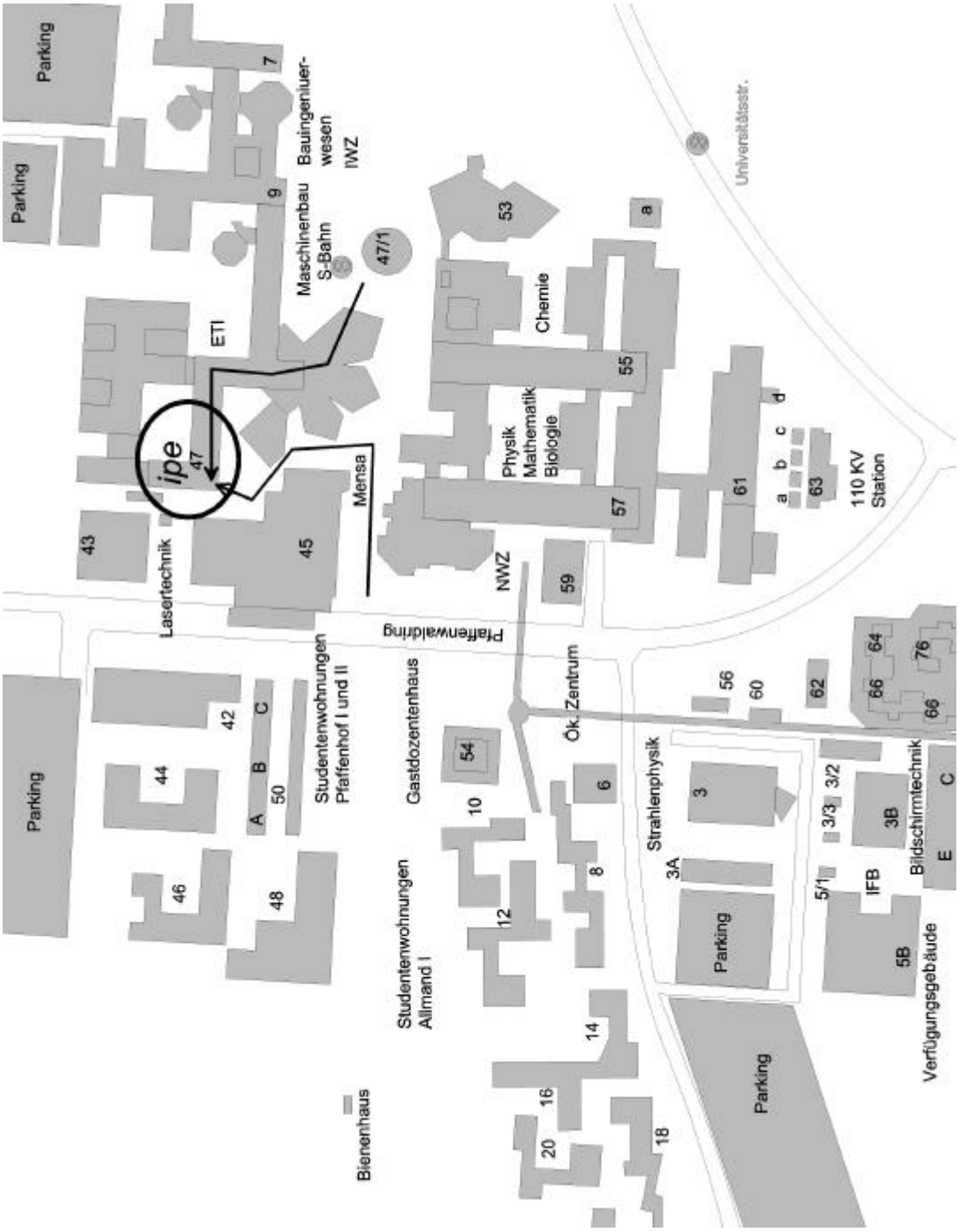
Name	**Titel**	**Tel**. 0711-685-...	**E-Mail** ...@ipe.uni-stuttgart.de	**Arbeitsgebiet**
BAUER, LEO		7182	bauer	Metallisierung, Photoarbeiten, Maskentechnik
BERGE, CHRISTOPHER	Dipl.-Phys.	7162	berge	Dünnschicht-Solarzellen aus kristallinem Silicium
BILGER, GERHARD	Dr.-Ing.	7176, 7154	bilger	Oberflächenanalytik mit SIMS und XPS; Technologie-Support
BRENNER, KLAUS	Dipl.-Ing. (FH)	7201	brenner	Technologische Infrastruktur und Prozesse der Si-Technologie
BRÜHNE, KAI	Dipl.-Phys.	7170	bruehne	Hot-Wire Deposition von nanokristallinem Silicium
CRAFF CASTILLO, CECILIA	Dipl.-Phys.	7160	craff	Rapid Thermal CVD, epitaktisch hergestellte p-n-Übergänge
CAO, XINMIN	Dipl.-Ing.	7161	cao	Silicium-Epitaxie
DEMIR, JAKOB	Dipl.-Ing.	7163	demir	Herstellung und Charakterisierung von Dünnschichttransistoren
DOLCH, THOMAS		7182	dolch	Sputtern von TC-Schichten, Elektrik, Elektronik
EMELIANOV, VITALI	Dipl.-Phys.	7183	emelianov	Elektrisches Rauschen an Halbleitern
GEBHARDT, KERSTIN	Dipl.-Phys.	7142	gebhardt	Oberflächenanalytik mit XPS, Heterostrukturen
GEMMER, CHRISTIAN	Dipl.-Phys.	7198	gemmer	Gestapelte Solarzellen aus amorphem und nanokristallinem Silicium
GLÖCKNER, JÖRG	Dipl.-Ing.	7179	gloeckner	Dünnschichtphotodioden für Kameraanwendungen
GRABITZ, PETER	Dipl.-Phys.	7197	grabitz	Flexible Verbindungshalbleiter-Solarzellen
HANNA, GEORGE	Dipl.-Phys.	7171	hanna	Hochleistungs-Cu(In,Ga)Se_2-Solarzellen, Abscheidung und Analyse von CIGS
HARTMANN, MARTIN	Dr. rer. nat.	7184	hartmann	Dünnschichttechnik; Herstellung und Charakterisierung von CIGS
JASENEK, AXEL	Dipl.-Phys.	7178	jasenek	Strahlenschäden in CIGS-Solarzellen
KOCH, CHRISTIAN	Dipl.-Phys.	7155	koch	Niedertemperaturabscheidung von amorphem Si
KÖHLER, CHRISTIANE	Dipl.-Phys.	7182	ckoehler	Si-Niedertemperaturtechnologie, XRD, transparente Kontakte, Ramanstreuung
KÖHLER, JÜRGEN	Dr.-Ing.	7159	jkoehler	Laser Annealing, Verwaltung

KÖTSCHAU, IMMO	M.Sc.	7171	koetschau	Oberflächenmodifikationen von Chalkopyrithalbleitern
KRON, GREGOR	Dipl.-Phys.	7160	kron	Organische Farbstoff-sensibilisierte Festkörpersolarzellen
KÜHNLE, DENNIS		7200	kuehnle	Aufdampfen von Halbleiterschichten
LAPTEV, VIKTOR	Dr. rer.nat.	7197	laptev	Chemische Schichtabscheidung, Röntgenbeugungsmessungen
LUTZ, BRIGITTE		7200	lutz	Analytik, Elektrochemie, GCMS
NGUYEN HONG QUANG	M.Sc.	7171	quang	Oberflächenchemie von Cu(In,Ga)Se_2 , Pufferschichten
NGUYEN XUAN VIET	M. Sc.	7179	viet	a.Si:H/c-Si Heterostrukturen
ORGASSA, KAY	Dipl.-Phys.	7181	orgassa	Optische Optimierung von CIGS-Solarzellen
PFISTERER, FRITZ	Dr.-Ing.	7157	pfisterer	Organisation / Verwaltung / allgemeine Aufgaben / Lehre (Optoelektronik I)
RAKHLIN, MICHAIL	Dipl.-Phys.	7183	rakhlin	Thermoelektrik, Silizium-Germanium-Dünnschichten
RAU, UWE	Dr. rer. nat.	7199	rau	Elektrische Charakterisierung und Modellierung von Dünnschichtsolarzellen (CIGS, Si, org.), Jahresbericht
REISMAYR, DIETER	Dr.-Ing.	7142	reismayr	Photovoltaische Systemtechnik, PV-Praktikum
RENNEBARTH, NILS	Dipl.-Math.	7162	rennebarth	Netzwerk
RINKE, TITUS	Dipl.-Ing.	7155	rinke	Solarzellen aus kristallinem Si
RIß, ANTON		7214	riss	Werkstatt
ROJAHN, MARTIN	Dipl.-Phys.	7179	rojahn	Herstellung und Verkapselung von Mikro-Photodioden aus a-Si:H
SCHOCK, HANS-WERNER	Dr.-Ing.	7180	schock	Dünnschichttechnik, Photovoltaik-Dünnschichtsolarzellen aus Verbindungshalbleitern
SCHUBERT, MARKUS	Dr.-Ing.	7145	schubert	Projektleitung amorphes und nanokristallines Si, Solarzellen mit Sensoren, Studien- und Diplomarbeiten, www.
SCHWARZMANN, PETER	Dipl.-Ing.	7167	schwarzmann	Multimedia in der Ausbildung, Telelearning, OLED
TARETTO-ZEYEN, KURT	Dipl.-Ing.	7181	taretto	Simulation und elektrische Charakterisierung von Halbleitern
TURCU, MIRCEA	M.Sc.	7184	turcu	Strukturelle und optische Eigenschaften von Cu(In,Ga)Se_2

WAGNER, THOMAS	Dipl.-Phys.	7161	wagner	Defektanalyse an Silicium-Niedertemperaturepitaxie-Schichten
WEINERT, KRISTIN	Dipl.-Phys.	7170	weinert	Elektrische und optische Charakterisierung von CIGS-Solarzellen
WERNER, JÜRGEN	Prof. Dr. rer. nat. habil.	7140	werner	Institutsleitung
WIESNER, HOLM	Dipl.-Ing.	7197	wiesner	CIS-Technologie
WILLE, WERNER		7158	wille	Buchhaltung, Verwaltung
WINTER, BIRGITT	Dipl.-Ing. (FH)	7200	winter	Technologie kristalliner Si-Solarzellen
ZAISER, INGE		7141	zaiser	Sekretariat, Verwaltung

13 Lageplan / *Site Plan*

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47
ETI
Maschinenbau
S-Bahn
47/1
Bauingenieur-
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IWZ
7
9
53
a
Chemie
55
Physik
Mathematik
Biologie
57
61
a b c d
63
110 KV
Station
Universitätsstr.
43
Lasertechnik
45
Mensa
NWZ
59
Pfaffenwaldring
Studentenwohnungen
Pfaffenhof I und II
Gastdozentenhaus
Ök. Zentrum
42
44
A B C
50
46
48
54
10
12
6
8
14
16
20
18
Bienenhaus
Studentenwohnungen
Allmand I
56
60
62
64
66
76
66
Strahlenphysik
3
3A
3/2
3/3
5/1
IFB
3B
Bildschirmtechnik
E
C
5B
Verfügungsgebäude