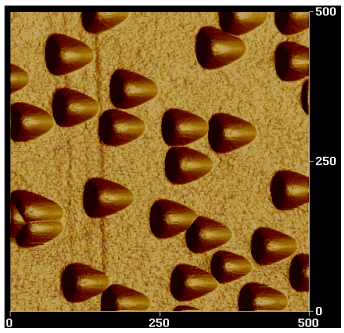
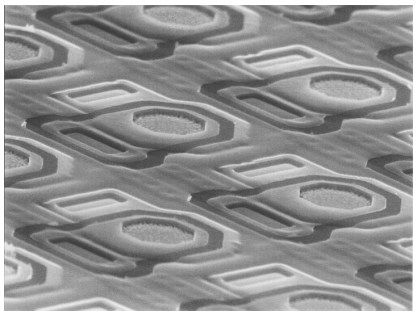
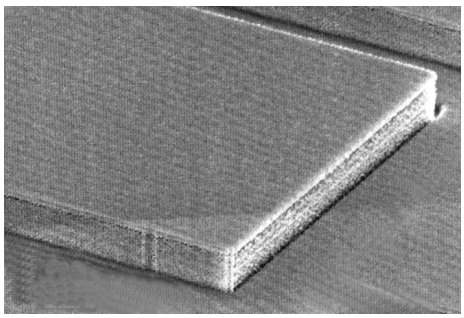
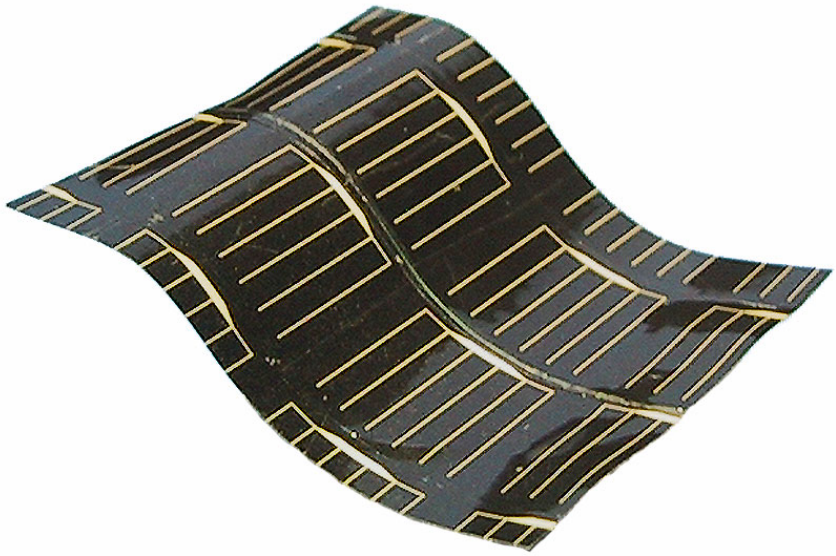
Annual Report

Thin Film Physics Group
June 2002









Cover page:

Top: PbSe quantum dots (500 nm x 500 nm) (left); partial view of a monolithic staring photovoltaic PbTe-on-Si IP-FPA with 5.5 μm cut-off wavelength (right);

Middle: Preliminary themal image (left); etched mirror face of a IV-VI laser structure on Si(111) (right);

Bottom: Flexible Cu(In,Ga)Se_2 solar cell on a polyimide sheet. Total thickness of the cells and substrate is 15 μm. Record efficiencies of 12.8% and 11.0% have been achieved for flexible Cu(In,Ga)Se_2 and CdTe solar cells, respectively.

CONTENT

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PERSONNEL (as of June 2002)

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Leader Photovoltaics:
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Derk Bätzner
Dr. Franz-Josef Haug
Marc Kaelin
Klaus Kellermann
Dr. Alessandro Romeo
Dominik Rudmann
Dr. Pradeep Srivastava
Dmitri Zimin

Technical Staff:
Thomas Kämpfer
Michael Leopold (60%)

Administrative Staff:
Paulette Pfammatter (20%)

Academic guests:

Alexander Banshchikov	(Ioffe Institute, St. Peterburg, Russia, Feb.-March 2002)
Matthias Terheggen	(Institute of Applied Physics, ETHZ)
Feodor Kurdesau	(Institute of Semiconductor Physics, Academy of Science, Minsk, Belarus)

GENERAL

The thin film physics group was integrated into the Institute of Quantum Electronics, Micro- & Optoelectronics Lab. (Head: Prof. Dr. H. Melchior) in May 1997, after the organisation AFIF (Arbeitsgemeinschaft für industrielle Forschung), to which the group belonged before, was closed. Since October 2000, after the retirement of Prof. Melchior, the group is with the Laboratory for Solid State Physics (Head: Prof. Dr. H.-R. Ott).

The group is financed exclusively by projects ("Drittmittel"), including all salaries

SPONSORS

ETH
European Space Agency
GRS
Swiss National Science Foundation
Swiss Federal Office for Education and Science (BBW, for EU-projects)
Swiss Commission for Technology and Innovation (KTI)
Swiss Defence and Procurement Agency (GR)
Industries

PROJECT COOPERATION

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Institute of Semiconductor Physics, Mins, Belarus
Central Solar Energy Laboratory, Sofia, Bulgaria
EMPA Dübendorf
INSAMET, San Sebastian, Spain

RESEARCH ACTIVITIES

Science and technology of compound semiconductors:

- Growth of molecular beam epitaxial (MBE) and polycrystalline layers of II-VI, IV-VI, I-III-VI_2, and III-V binary and multinary compounds. Applications for optoelectronic devices. Growth kinetics of heterostructures, superlattices and nano-structures (quantum dots). Phase formation and their identification.
- Structural properties of thin films, surfaces and interfaces. Crystallographic and microstructural defects. Lattice vibrational properties of semiconductors. Measurement and modelling of strain relaxation in thin films. Kinetics of dislocation-glide and -reactions in IV-VI-on-Si epitaxial layers. Recrystallization in semiconductors.
- Optical and electrical properties of thin films and heterostructures. In- and ex-situ doping in semiconductors, electronic defects and transport properties.
- Growth, properties and applications of transparent conducting oxides (ZnO, ITO, FTO).
- Growth and properties of permeation barrier layers ("flexible glass" on plastics).
- Thin film growth processes like molecular beam epitaxy, e-beam evaporation, d.c. and r.f. sputtering, chemical bath deposition, electro-deposition, etc.

Infrared sensors and emitters on silicon substrates:

- MBE growth of narrow gap IV-VI layers (lead chalcogenides) on Si-substrates.
- Fabrication of 1-d and 2-d IR sensor arrays; the Si-substrate may contain integrated read-out circuits.
- Development of microlithographic patterning techniques. Applications include thermal imaging and IR-spectrometry.
- Optically pumped edge emitting IV-VI lasers with 3-5 μm emission wavelength
- Optically pumped microcavity wavelength converter from 870 nm to 3-5 μm

Compound semiconductor thin film solar cells:

- Solar cells based on Cu(In,Ga)Se_2 and CdTe (these materials yield stable and very high efficiency solar cells for economical production of solar electricity). Development of material technologies, fabrication processes, novel materials and processes for improved performance, and advanced tandem devices. Interface and transport properties of heterojunctions.
- Studies of basic material properties and heterostructures for large area and industrial production. Stability and reliability of devices. Terrestrial and space applications of lightweight and flexible thin film solar cells.

Some highlights:

- Development of 1- and 2-dimensional infrared sensor arrays for thermal imaging in epitaxial PbTe on Si-substrates which contain active circuits
- Development of optically pumped IV-VI lasers on Si-substrates
- Development of optically pumped IV-VI microcavity wavelength converters on Si-substrates
- Flexible CdTe solar cells on polymers have been developed for the first time, and a record efficiency (11%) is achieved
- Long term stable and low resistance quasi-ohmic contacts on CdTe that yield 11% efficiency solar cells
- Lightweight and flexible Cu(In,Ga)Se_2 solar cells on polymer with a world record efficiency of 12.8%
- Electronic and structural comparison of Cu(In,Ga)Se_2 substrate and superstrate solar cells, 11% efficient supestrate solar cells have been obtained
- A low temperature deposition process for Cu(In,Ga)Se_2 solar cells; cells with 14% efficiency were achieved
- Highly transparent and conducting ZnO:Al layers with high deposition rates by RF magnetron sputtering

AWARDS

- D. Baetzner, shared with G. Agostinelli, "Young Scientist Award of Symposium B", E-MRS Spring Meeting, Strasbourg, June 18-21, 2002
- D. Baetzner, G. Agostinelli, "Best poster presentation", 29th IEEE Photovoltaic Specialists Conference, New Orleans, May 20-24, 2002
- F.-J. Haug "Young Scientist Award of Symposium P", E-MRS Spring Meeting, Strasbourg, June 5-8, 2001
- A. Romeo, "Student Silver Award", Mat. Res. Soc. Symp., April 16-20, San Francisco, USA, 2001

EQUIPMENT

4 MBE-chambers with solid sources for CaF_2, (Pb,Sn)Se, Cu(In,Ga)Se, and CdTe
6 PVD for sample sizes up to 20 x 20 cm^2, thermal and e-beam evaporation
3 sputtering chambers, DC and RF (substrate size up tp 30x30 cm^2)
Complete photolithographic processing equipment
Bonder
Profilometer
Light microscopy, SEM, XRD
Electrooptic characterization for infrared sensors/emitters and solar cells

Self assembled PbSe quantum dots on PbTe/Si(111) with near equal sizes

K. Alchalabi, D. Zimin, H. Zogg

Self assembled PbSe quantum dots (QD) were grown on a few μm thick PbTe(111) layers on Si(111). The QD form as pyramids with three (100) side faces and (111) base, i.e. with a very high aspect ratio. After overgrowth with 4 ML, about 100 dots μm^{-2} form with heights of about 16nm. The heigths of a large number of dots were determined with AFM. Since all dots exhibit the same shape, their volumes are determined by one parameter (e.g. the heights) only.The observed distribution of these heights (and therefore the volumes of the dots) is extremely narrow: The standard deviation of the heights as measured by AFM can be as low as 2%. This seems to be the narrowest distributions ever observed for self assembled quantum dots.

Similar PbSe quantum dots with pyramidal shapes have first been described by Pinczoltis et al. (Applied Phys. Lett. 73, 1998, p. 734). These authors used cleaved BaF_2 as a substrate. They observed two types of dots and with somewhat larger size distributions, however.

The results are explainable on the basis of nucleation and growth theories.

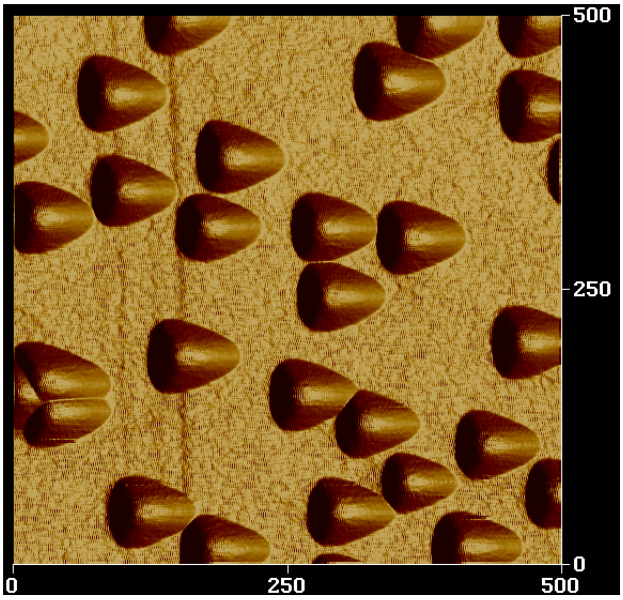


Figure: AFM micrograph of pyramidal qutum dots with 16 nm heigths and size nonuniformities as low as 2%.

Sponsor: Swiss National Science Foundation

Monolithic heteroepitaxial PbTe-on-Si infrared focal plane array with 96 x 128 pixels

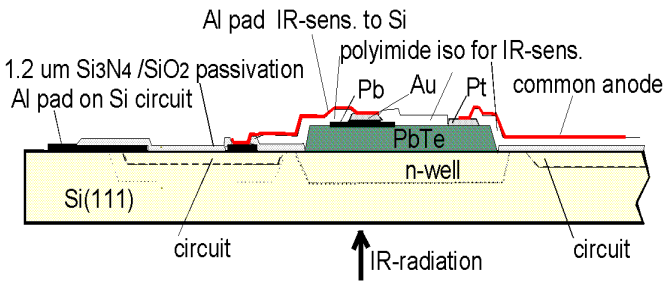
K. Alchalabi, D. Zimin, H. Zogg

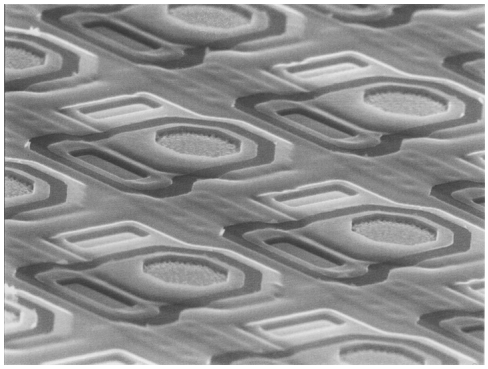
A two-dimensional infrared focal plane array in a heteroepitaxial narrow gap semiconductor layer has been realized for the first time on a Si substrate containing the read-out electronics, and thermal images are demonstrated.

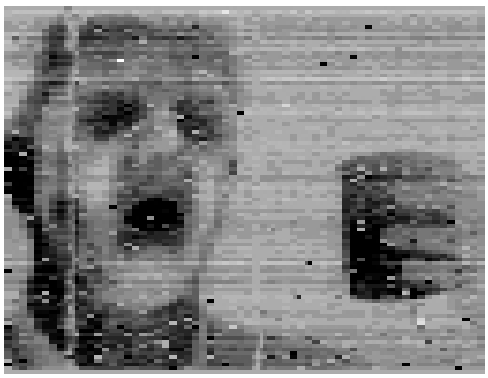
CMOS technology was used to fabricate the circuitries in the Si-substrate. Pitch is 75 μm, each pixel contains a bare Si-area where epitaxial growth of the narrow gap layer occurs, and an access transistor. Addressing is performed line-by-line with a shift-register integrated on the chip.

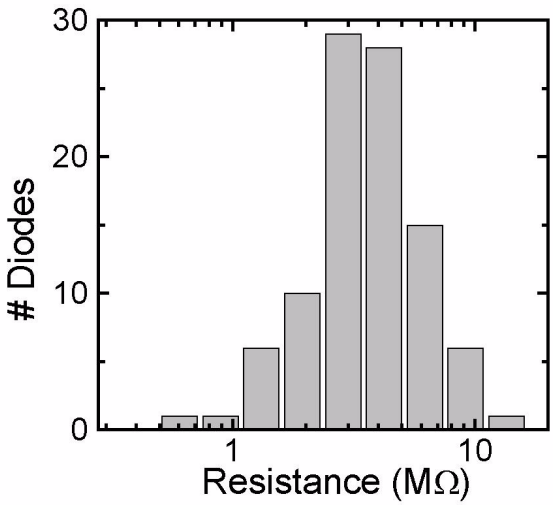
The infrared-sensitive layer (PbTe for the 3-5 μm wavelength range) is grown by molecular beam epitaxy at temperatures below 450°C, allowing fully processed and tested Si chips to be employed. Individual pixels are obtained by mesa-etching, and photovoltaic sensors are fabricated with standard photolithographic techniques.

Within the >97% operational pixels, high quantum efficiencies and differential resistances at zero bias with 4 M Ω mean value at 95K are observed. these values are much above the background noise limit for room temperature radiation.









Figures. Schematic cross section (left), part of the 2-d array (middle), demonstrational thermal image at 95K of the 96 x 128 PbTe-on-Si array with 5 μm cut-off wavelength (bottom) and differential resistances (sensitivities) of the sensor (below).

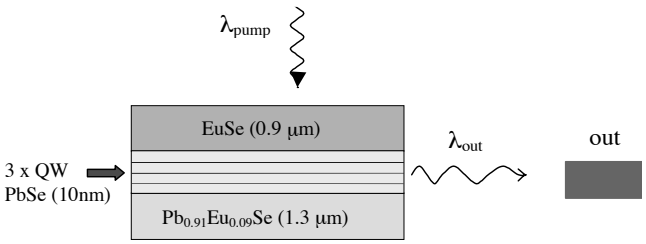
Sponsor: GR, KTI

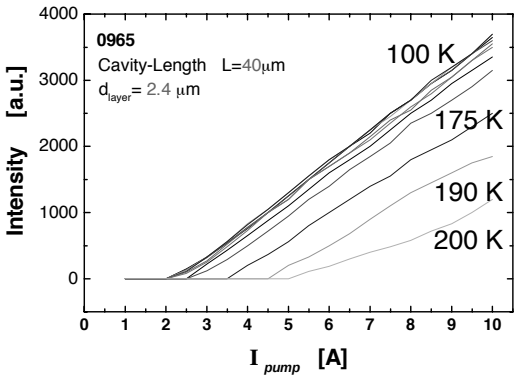
Optically pumped IV-VI edge emitting IR-lasers

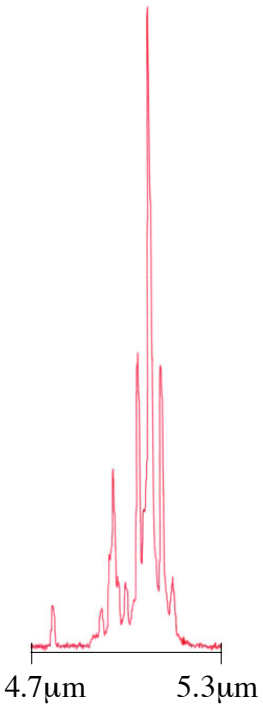
K. Kellermann, D. Zimin, K. Alchalabi, H. Zogg

With the advent of compact high-power laser diodes with around 900 nm or 1500 nm emission wavelength, low-cost optically pumped lead chalcogenide IR-emitters for wavelengths above 3 μm become attractive. In addition, the low Auger recombination of the lead chalcogenides is highly advantagous

DH (double heterostructure) and QW structures are grown by MBE on Si(100) substrates with the aid of a BaF_2 buffer layer. The structures typically consist of a bottom $Pb_{1-x}Eu_xX$ (X = Se or Te) cladding layer, the active $Pb_{1-y}Eu_yX$ layer containing PbSe QWs, and a top EuX cladding layer which is transparent to the incoming 870 nm laser beam. The about 2-3 μm thick layers are lifted-off from the substrate by dissolving the BaF_2, cleaved into pieces of e.g. 2000 x 40 μm size and clamped between a heat-conducting substrate and a glass cover. The light of the 870 nm laser diode (typically up to 10W pulsed) is focused onto the structure and the lasing characteristics are determined. Up to now, we observed lasing up to about 240K with this limited power and without a lateral confinement. These lasers exhibit high characteristic temperatures T_o up to 125K. This despite dislocation densities are as high as 10^8 cm^{-2}. We expect room-temperature operation if higher quality layers are used. Such layers result e.g. when using BaF_2(100) or bulk PbX(100) as a substrate. In addition, we presently develop etched mirror faces (see figure on cover for a homostructure); with etched faces we can use (111) oriented layers on Si. These layers are of much higher quality (one to two orders of magnitude lower dislocation densities as compared to layers on Si(100) due to the easy glide of the dislocations in their main {100} glide planes).







Figures: Structure of an optically pumped edge emitting IV-VI IR-laser (top), the light-in - light-out characteristics (bottom) and a typical spectrum (right).

Sponsor: GRS , ETH

Vertical emitting optically pumped IV-VI IR-microcavity

K. Kellermann, D. Zimin, K. Alchalabi, H. Zogg

A "wavelength transformer" downconverting part of the incoming 870 nm light to about 4 μm wavelength was realized. It has a similar structure as a VCSEL (vertical cavity surface emitting laser), but with much lower reflectivity top and bottom mirrors: A $\lambda/2$ PbEuSe active layer containing PbSe QW (quantum wells) is sandwiched between the two Bragg mirrors and illuminated from the top with a 870 nm III-V laser diode. The top Bragg mirror consists of e.g. 2 pairs of EuSe/BaF2 which are transparent to the incoming light, the bottom mirror of e.g. 1 pair PbEuSe/BaF_2. Reflectivities are between 85% and 95%. The device works at RT in the subthreshold region. Its line width is given by the resonator design, about 4% for the present application for low-cost gas sensing. The whole structures are grown by MBE on Si(111) or BaF_2(111) substrates, the substrates are transparent to the output beam and also act as a mechanical protection.

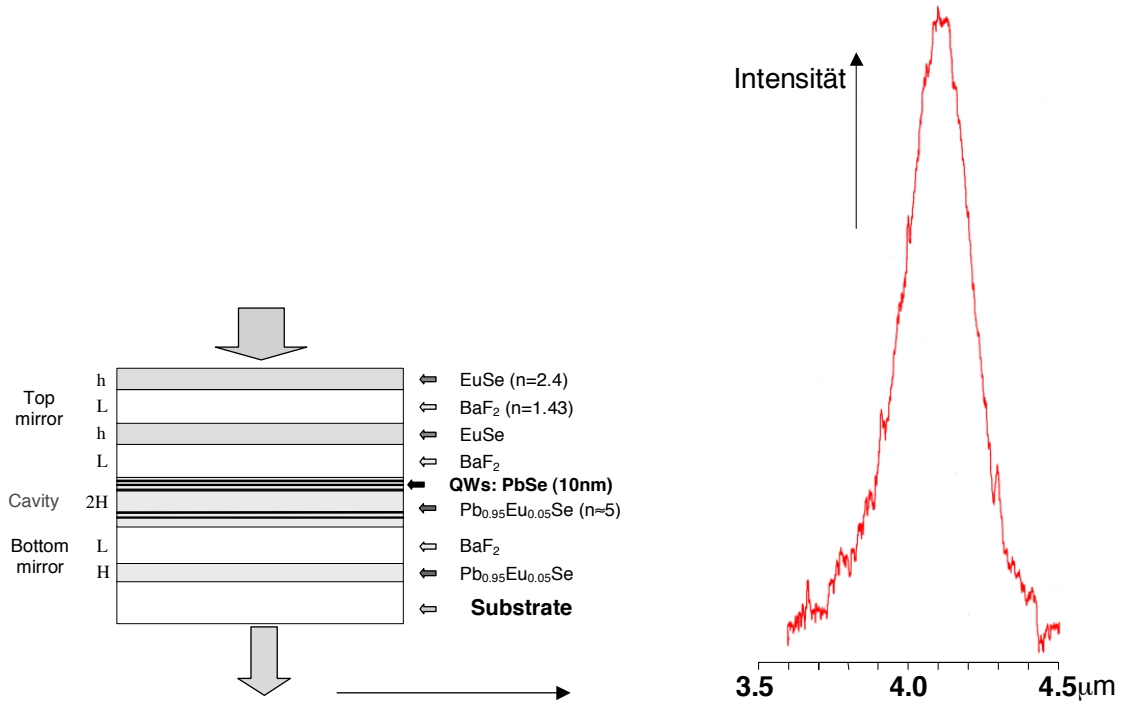


Fig. Schematic structure of an optically pumped microcavity mid-IR-source and emission characteristics.

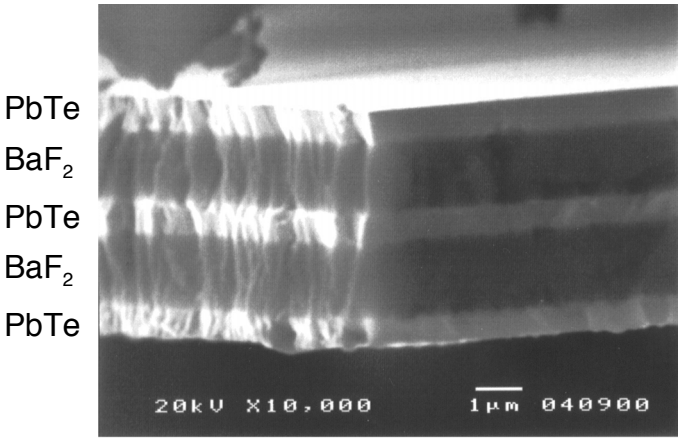
Sponsor: GRS

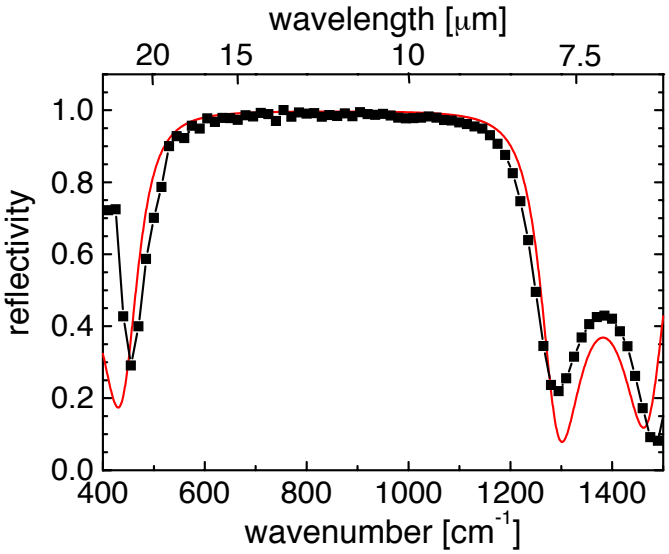
Broad-band high reflectivity Bragg mirror for the mid-infrared range

K. Kellermann, D. Zimin, K. Alchalabi, H. Zogg

We fabricated high reflectivity Bragg-mirrors using alternating layers with high and low refractive index arranged in a quarter wavelength stack. BaF_2 (n=1.4) served as low index and PbTe (n=5.5) as high index material, respectively. This large index difference leads to a high reflectance with already few layers, and the spectral response is extremely broadband.

The layers are grown by molecular beam epitaxy onto Si(111) substrates using solid sources. Fig. 1 shows an image of the stack. The measured reflectivity is shown in fig. 2, together with the calculated curve. The reflectivity is above 98% (Measurement uncertainties 2%) from about 9 μm to 16 μm wavelength.





The mid-IR range is extremely suited for trace gas analysis. The mirror will be applied for one analysis method, cavity ringdown (see report of Prof. M.W. Sigrist, Lab. for Laser Spectroscopy and Environmental Sensing). As a side result of this method, the absolute reflectance at selected wavelengths is obtained with much higher accuracy, as needed for the calibration.

Fig. 1 (top)
BaF_2/PbTe 5 layer Bragg-mirror structure for the mid-IR range.

Fig. 2 (bottom)
Measured (squares) and calculated (full line) reflectance of the BaF_2/PbTe Bragg mirror.

Sponsor: GRS

Development and electrical characterisation of Cu(In,Ga)Se_2 superstrate solar cells

F.-J. Haug, D. Rudmann, H. Zogg, A. N. Tiwari

For thin film solar cells two configurations are distinguished: the substrate and the superstrate solar cell. Solar cells with Cu(In,Ga)Se_2 absorber layers are usually prepared in the substrate configuration. Efficiencies of up to 18.8% are obtained with a CdS buffer layer which requires a wet chemical process. All dry processed substrate solar cells reach efficiences of up to 16.2%.

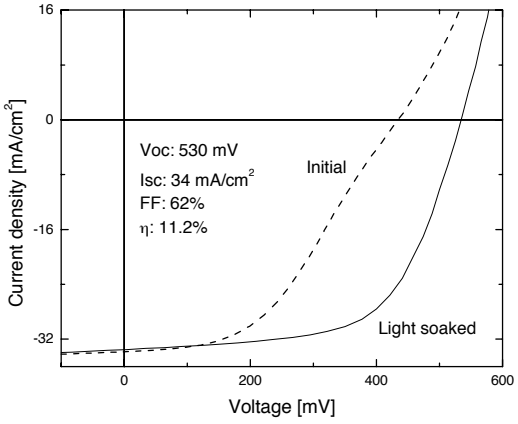
Cu(In,Ga)Se_2 soalr cells in superstrate solar cells exhibit lower efficiencies, however, this configuration is advantageous because in involves only dry process steps and it offers easier encapsulation, therefore giving rise to lower manufacturing costs. Superstrate solar cells show metastable illumination effects, the j-V characteristics considerably improve upon illumination (see below). We have achieved superstrate solar cells with efficiencies of up to 11.2% after light soaking.

For further improvements it would be desirable to know if the performace is limited by bulk or interface properties. A method to study the transport mechanism is the analysis of the saturation current j_0 at different temperatures:

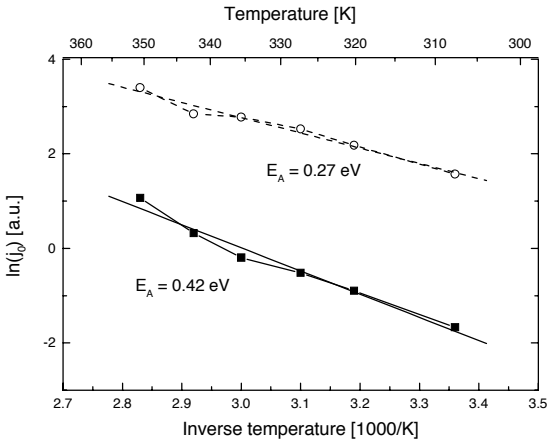
$$j(V) = j_0 e^{\frac{qV}{AkT}} = j_{00} e^{\frac{qV - E_A}{AkT}}$$

The absolute temperature is denoted by T, k is the Boltzmann konstant, j_{00} is the saturation current density prefactor. After correction with the diode quality facor A the activation energy E_A corresponds to the bandgap in case of bulk dominated recombination processes or the barrier at the interface in case of interface recombination processes.

The diode quality factors before and after light soaking are about 2.4 and 1.6, respectively. Thus, the corrected activation energies of the Arrhenius plots yield approximately the same value of 650 mV. With a bandgap of 1.2 eV this suggests predominant interface recombination. Future developments should therefore aim at improvements of the interface.



Current voltage characteristics before and after light soaking.



Arrhenius plot of the saturation current density before and after light soaking.

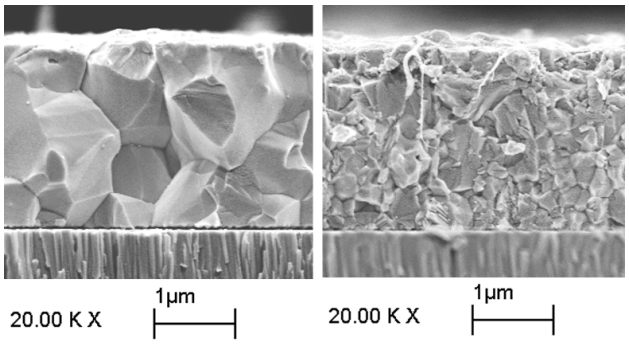
Sponsor: Gebert Rüf Foundation

Effects of Na on structural properties of $Cu(In,Ga)Se_2$ thin films

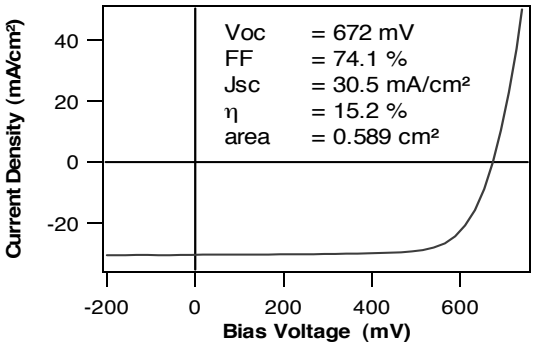
D. Rudmann, M. Kaelin, F.-J. Haug, F. Kurdesau, P.K. Srivastava, H. Zogg, A.N. Tiwari

Flexible $Cu(In,Ga)Se_2$ (CIGS) solar cells/ modules are interesting for terrestrial applications, especially when the rigidity or weight of modules encapsulated with glass plates causes problems for installation. Also for space use flexible CIGS solar cells are very attractive due to the savings in weight of deployment constructions and due to excellent resistance of CIGS solar cells against proton and electron irradiation. As substrates for flexible solar cells primarily polyimides and metal foils can be used. In general, none of them contain sodium. Na is known to have beneficial electronic influences on CIGS solar cells, therefore, we have investigated alternative methods of Na incorporation into CIGS and examined structural effects on the material.

Different amounts of coevaporated NaF have been used during different stages of CIGS growth and using different methods. The results show that the Na concentration in CIGS can be varied with NaF coevaporation, while F cannot be detected in the films. An influence of Na on the reaction kinetics is observed. The texture of CIGS has not been found to be influenced by Na, except when NaF precursors have been used. A further effect of Na observed is that the CIGS grain size becomes smaller with increasing Na concentration (see figure). This phenomenon is independent of the Na incorporation method used. A large grain size would be preferable since grain boundaries are potential recombination centres in an absorber. On the other hand, Na seems to passivate defects at grain boundaries, which leads to a strong enhancement in the electronic properties of CIGS. Cell performance indicates that the electronic benefits induced by Na are more important than a large CIGS grain size. Solar cells with an efficiency exceeding 15 % ($\eta = 15.2$ %, $V_{OC} = 672$ mV, FF = 74.1 %, $J_{SC} = 30.5$ mA/cm², area = 0.589 cm², no antireflection coating) have been obtained with Na containing CIGS absorber layers (see Fig. 2).



Cross-section SEM micrographs of CIGS layers without (left) and with (right) Na.



I-V characteristics of a 15 % CIGS solar cell.

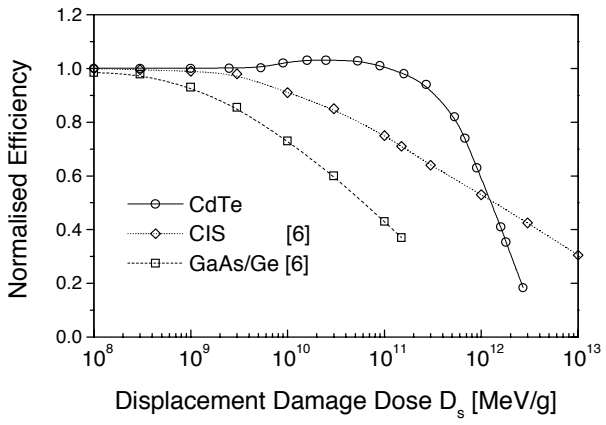
Acknowledgements

The authors would like to thank P. Wägli for SEM pictures.

Sponsor: BBW (EU Project), Swiss National Science Foundation

Radiation hardness and impurity degradation of CdTe/CdS solar cells

D.L. Bätzner, A. Romeo, A. N. Tiwari, H. Zogg



CdTe/CdS solar cells have a promising potential for space application due to their high specific power, i.e. power per weight, on thin and flexible substrates and excellent radiation hardness. We investigated the radiation tolerance of CdTe/CdS solar, which have been developed in our lab with a process capable of deposition on flexible substrates, in detail by irradiation with protons (at the TANDEM accelerator of PSI/EHTZ) and electrons (at the DYNAMITRON electron accelerator of the University of Stuttgart). The cells have been irradiated with very high fluences of the particles different energies in the MeV, equivalent to exposures of decades in space. The displacement damage dose formulation was applied to determine one single degradation characteristics as a function of damage dose, that contains the data of all particles, energies, and fluences.With this formulation it was possible to compare the CdTe solar cell technology in terms of radiation hardness to other technologies (see figure). CdTe is superior to the currently used mono-crystalline technologies (Si and group III-V compounds) and at medium doses to the thin film CIS technology. The CdTe cells also recover fast from the damage, which implies that for operation in space no performance degradation due to radiation damage is expected.

The stability of CdTe solar cells is still an issue and depends crucially on the impurities in the device. SIMS measurements indicate the impurity diffusion from back contact material into the CdTe bulk and the CdS with accumulation in the CdS layer or near the CdTe/CdS interface. To correlate these observations of changed chemistry in the cell with the photovoltaic properties, i.e. generally degradation, the technique of voltage dependent quantum efficiency measurement (referred to as Apparent Quantum Efficiency, AQE) was developed and applied to thermally stressed cells. In order to understand and interpret the AQE measurements a novel model was developed. The measurements indicate diffusion of Cu and Au into the CdTe cell resulting in degradation, whereas Sb and Mo may diffuse only in much smaller quantities and degrade the PV properties much less. Stable CdTe cells with Sb/Mo back contacts have been demonstrated, however, degradation derives also from further impurities contained in the source material.

Sponsor: BBW (EU-Project), European Space Agency

CIGS solar cells developed with evaporated II-VI buffer layers

A. Romeo, H. Zogg and A. N. Tiwari

High efficiency CIGS solar cells have been obtained with chemical bath deposited (CBD) buffer layers. However, for in-line production of modules vacuum deposition processes (PVD) are preferred for compatibility reasons and high throughput. We studied the possibility of obtaining high efficiency CIGS solar cells with all-dry processes. $Cu(In,Ga)Se_2$ absorbers were provided by IPE and ZSW in Stuttgart. Three different buffer layers were considered: CdS and as an alternative ZnS and ZnSe in order to reduce the optical absorption losses.

CdS was deposited by high vacuum evaporation at a substrate temperature of about 50°C, chemical or thermal surface cleaning treatments were not applied.

Solar cells prepared with 80 nm thick PVD-CdS yield an efficiency of 10 to 12%, while for CBD-CdS 14.6% efficiency has been obtained (see figure1). ZnS and ZnSe buffer layer were applied as alternative to CdS. Layers of different thickness were grown by e-beam evaporation at different substrate temperatures (RT to 400 °C). ZnS shows a very high transparency superior to the conventional buffers ZnSe and CdS.

PV performance depends on the properties of buffer layers, post-deposition annealing and light soaking conditions. Thin buffer layers of ZnS grown at a temperature of 150°C and after annealing in vacuum at 300°C yield cells with Voc exceeding 500 mV and FF of 63%.

It has been observed that diffusion of Zn into the CIGS is an important issue for high efficiency cells. If no post-deposition annealing of ZnS is applied than light soaking of the finished device improves the electrical properties, on the other hand a post deposition treatment gives the same results without applying light-soaking.

Up to now efficiency of about 7% were obtained for cells made with ZnS buffer layers and 6% for ZnSe buffer layers (see figure 2).

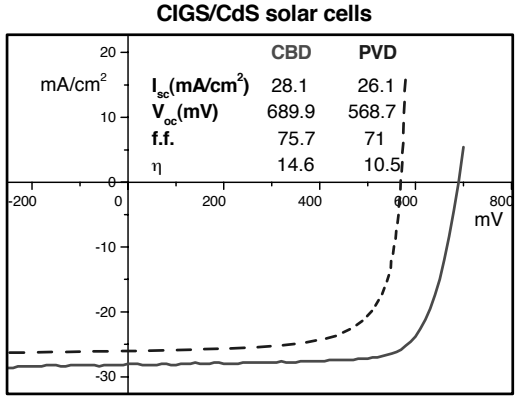


Figure 1. Comparison of CIGS solar cells with CBD and PVD CdS

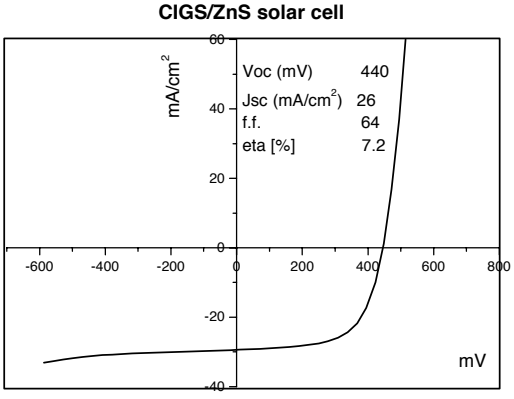


Figure 2. I-V of CIGS/ZnS solar cell.

Sponsor: BBW (EU-Project)

High efficiency flexible CdTe/CdS solar cells

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Development of flexible and lightweight solar cells is interesting for many terrestrial and space applications that require a very high specific power (defined as the ratio of output electrical power to the solar module weight). We presented a novel process for developing CdTe solar cells on polyimide film substrates. The polyimide layer was spin coated on glass prior to the deposition of ZnO:Al, and the semiconducting layers are grown at low temperatures, around 400°C. Further development of the transparent conducting oxide (TCO) resulted in a record efficiency of 11% for CdTe flexible cell with V_{oc} = 842 mV, I_{sc} = 18.5 mA/cm^2, and FF = 70.9%. For space applications it is desirable to avoid polyimides because of their possible degradation under UV light.

A novel process for preparing flexible CdTe solar cells was indicated. A layer of NaCl is deposited on glass prior to the deposition of TCO. Polyimide is spin coated on top of the layer (substrate configuration) so that it will still hold the solar cell but it will not be exposed to radiation. After the deposition of the stacks, a lift-off process is applied. Solar cells of 7.3% efficiency with V_{oc} = 692 mV, I_{sc} = 21.5 mA/cm^2, and FF = 49% were obtained.

Sponsor: BBW (EU-Project), European Space Agency

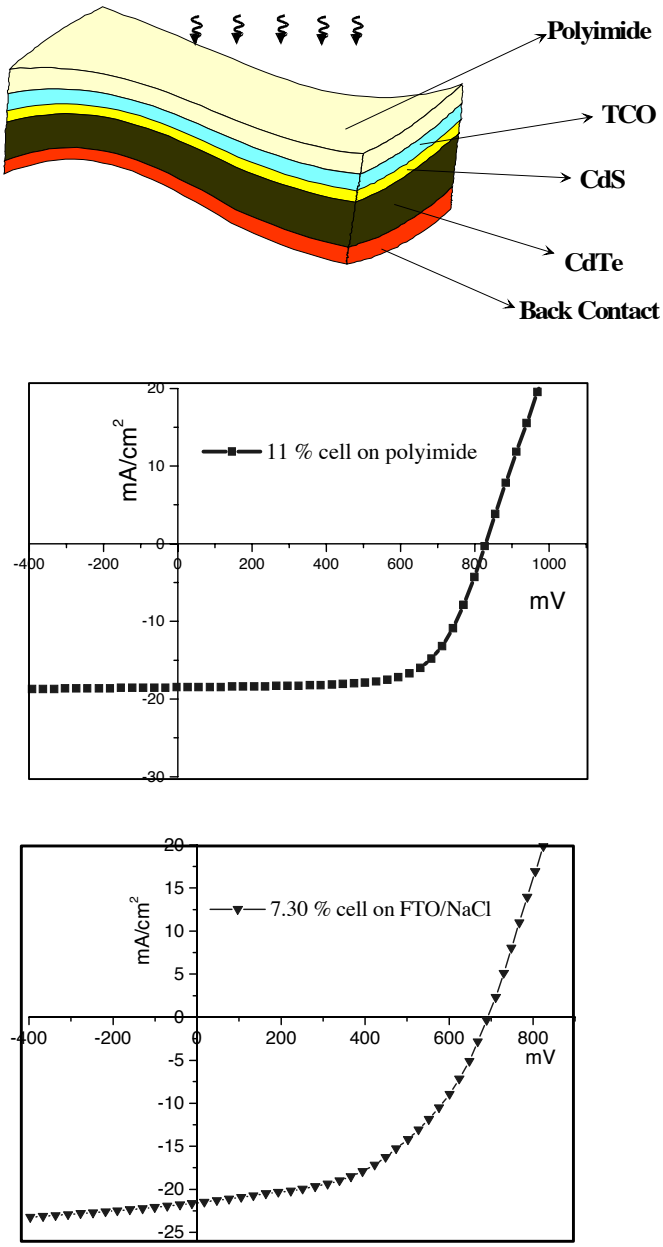

Figure1. Schematic cross-section of the flexible CdTe solar cell on polyimide in superstrate configuration (top) and I-V characteristic of a 11% efficiency CdTe solar cell on polyimide (superstrate configuration) measured under AM 1.5 illumination (middle) and of a 7.3% efficiency CdTe solar cell on polyimide (substrate configuration) (bottom).

Non-vacuum $CuInSe_2$ layers from selenized nanoparticle precursors

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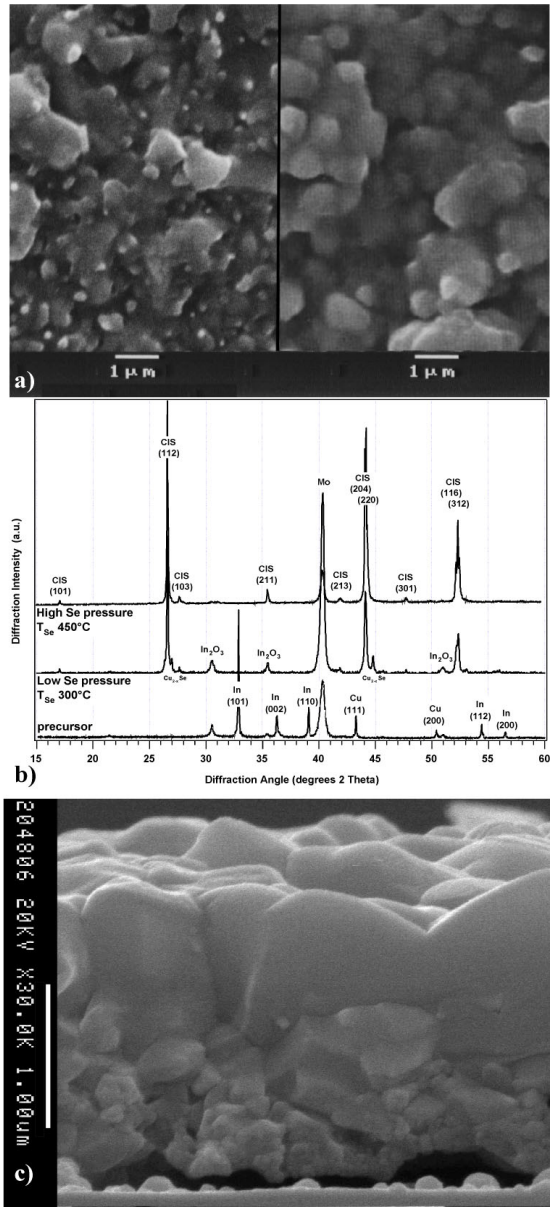
In order to reduce process complexity and costs of solar cells simple and low cost deposition methods are required. Advances in nanoparticle technology opened new perspectives in low-cost thin film processing. In combination with the established selenization technique these methods allow solar cell production without the requirement of expensive vacuum deposition systems. The chemical conversion (selenization) of nano-sized precursor materials into CuInSe2 (CIS) and Cu(In,Ga)Se2 (CIGS) compounds and microstructural properties of these layers have been investigated.

Uniform deposition of thin compact layers is a key issue in this novel method. The precursor layers were deposited on Mo coated glass substrates by doctor blade, screen printing and electrospray. Three categories of nanoparticles, namely metal-oxides, metal-selenides and elemental metal particles were selenized in selenium vapour under different selenium vapour pressures. While oxide and selenide precursors show limited sintering and chemical conversion, dense CIS layers with large grains (~1-2 μm) were obtained with metal precursors (see fig.1).

Higher selenium pressure reactions result in a better conversion of the oxide impurity phases that are introduced during the non-vacuum precursor film deposition.

Sponsor: KTI (TOPNANO 21)



Figures: (a) SEM micrograph showing the morphology of the selenized precursor film under high (left) and low (right) selenium pressure. (b) XRD patterns of the precursor- and selenized film under different selenization conditions. (c) Cross-section SEM micrograph of selenized film.

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