# Light-emitting devices in industrial CMOS technology

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**Abstract**

Two different unmodified industrial CMOS processes have been used for the integration of highly interdigitated pn structures Under forward bias these pn junctions emit narrow-band infrared light at 1160 nm with an electrical-to-optical power conversion efficiency of typically $10^{-4}$ The same junctions show broad-band visible-light emission between 450 and 800 nm in the avalanche breakdown region under reverse bias with efficiencies of the order of $10^{-8}$ This is already enough for a first few practical applications as light-emitting devices (LEDs) No satisfactory explanation for this emission effect, fitting all the experimentally observed electro-optical and physical properties of our silicon LEDs, has been found yet

## 1. Introduction

It has been shown [1] that the integration of photodetectors with analog and digital electronics in standard CMOS technology is feasible This opens up the opportunity to fabricate small and inexpensive optical metrology and sensing systems However, in various applications of such devices, controlled illumination is required or at least useful to reduce the amount of data processing needed Integration of light sources in silicon is considered to be impractical, since silicon has an indirect band gap, implying that light-emitting devices (LEDs) are very inefficient Furthermore, normal forward-biased LEDs emit narrow-band radiation at energies near the band gap [2], where photodiodes of the same material are insensitive and therefore not suitable for detection Hybrid integration with a layer of different material grown onto the silicon chip is expensive and difficult to achieve, because of the lattice mismatch at the interface, which causes the formation of defects

Recently, visible photoluminescence [3, 4] and electroluminescence [5] have been obtained in silicon nanostructures (porous silicon) Unfortunately, fabrication of such structures involves an electrochemical treatment step, which is not available in standard silicon technology Our work is motivated by much older observations of broad-band visible and infrared light emission from silicon diodes operated near avalanche breakdown [6, 7]

## 2. Device structures

Two industrial CMOS processes have been used for the integration of silicon LED structures One of them is SACMOS-3 offered by FASELEC Ltd [8], a simple p-well process (single poly, single metal) with 3 μm design rules and self-aligned contacts, the other is the 2 μm FORESIGHT n-well process (double poly, double metal) by Orbit Semiconductor Inc [9] Both processes are available in inexpensive multi-project wafer services

In the SACMOS-3 process the estimated doping concentrations are $10^{15}$ cm$^{-3}$ for the n-substrate, $1.5 \times 10^{16}$ cm$^{-3}$ for the p-well, $10^{19}$ cm$^{-3}$ for the $p^+$ implant, and $3 \times 10^{19}$ cm$^{-3}$ for the $n^+$ implant The depths of the $p^+$ and $n^+$ layers are 0 6 and 0 5 μm, respectively LEDs have been realized using interdigitated structures of the $p^+n^-$, $n^+p^-$ and $p^+n^+$ junctions, each with a period of 12 μm Cross sections are shown in Fig 1(a)–(c) The $p^+n^-$ and $n^+p^-$ structures measure 100 μm across and 50 μm along the fingers, the $p^+n^+$ structure 120 μm across and 20 μm along the fingers

In the FORESIGHT process only a $p^+n^-$ LED has been implemented (Fig 1(d)) Doping concentrations and junction depth are similar to those of the SACMOS-3 $n^+p^-$ diode The period of the interdigitated structure is 25 μm and the total area 100 μm × 100 μm

## 3. Experimental

The $n^+p^-$ diode was operated at forward voltages of up to 1 2 V, corresponding to a maximum forward current of 100 mA The spectrum as measured with a Fourier transform spectrometer is shown in Fig 2 It exhibits a single peak at a wavelength of 1160 nm with a full width at half maximum of 70 nm The power conversion efficiency, defined as the ratio of electrical input power and optical output power, and quantum

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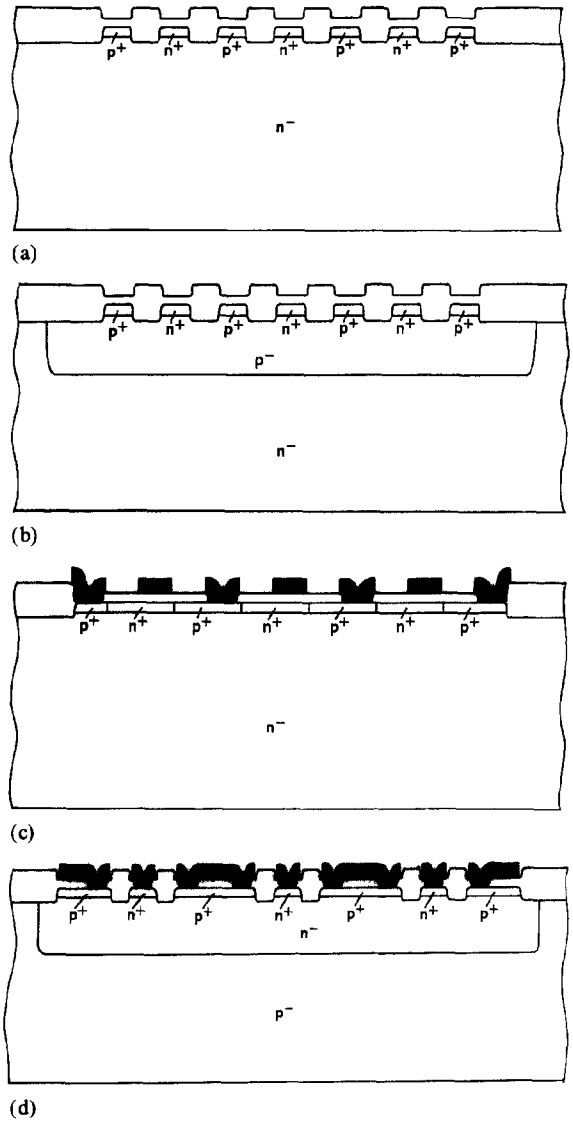


Fig 1 Cross sections of light-emitting diodes (LEDs) in industrial CMOS processes (a) SACMOS-3 $p^+n^-$ LED, (b) SACMOS-2 $n^+p^-$ LED, (c) SACMOS-3 $p^+n^+$ LED, (d) FORESIGHT $p^+n^-$ LED The $p^+$ and $n^+$ fingers in (a) and (b) are contacted at their ends, whereas those in (c) and (d) are covered by metal lines to which they are contacted periodically

efficiency, i e , the number of photons produced per electron crossing the junction, both amount to around $10^{-4}$ and do not vary significantly with the forward current The emitted radiation has a mean energy of 1 07 eV, which is slightly smaller than the silicon band-gap energy of 1 12 eV As expected, no radiation is observed at energies significantly higher than the band gap, where silicon photodiodes are sensitive

When operated at reverse bias, all structures show roughly the same behaviour in the vicinity of avalanche

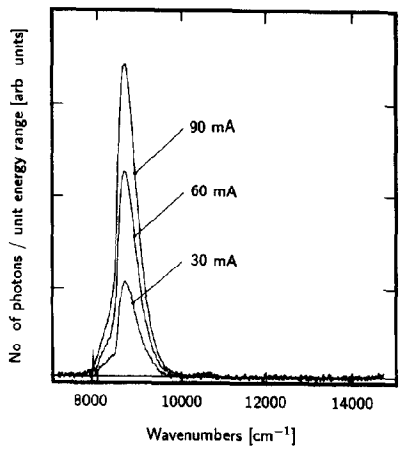


Fig 2 Emission spectrum of the SACMOS-3 $n^+p^-$ LED operated in forward bias for three different input currents A single peak at a wavelength of 1160 nm with a FWHM of 70 nm is found

breakdown, small yellowish-white or reddish-white light spots appear where the junction reaches the silicon surface at different locations with inhomogeneities, e g , near contact corners With increasing reverse current the spots grow brighter until they saturate and more spots start to appear Finally, the spots connect to lines along the junction In more homogeneous regions the entire junction edge lights up at once The effect is reproducible in that the same spots always appear at the same current level The diameter of the spots is too small to be resolved by a conventional light microscope The spots are bright enough to be easily visible with the unaided eye under ambient room illumination The emission spectra were measured with a SPEX-100 spectrometer and are shown in Fig 3(a)–(d) as quantum efficiencies (or number of emitted photons) per unit wavelength interval in arbitrary units on a linear scale The polarization of the observed light is predominantly perpendicular to the junction edge The total power conversion and quantum efficiencies for radiation with wavelengths below 850 nm with some typical current/voltage settings are shown in Table 1 The efficiencies are only weakly dependent on these settings, however

## 4. Discussion

The results for operation at forward bias confirm the theoretical predictions and previous measurements [2] Since silicon photodiodes are insensitive to the emitted radiation, the field of applications of such light sources for integrated optical metrology systems is limited

The spectra obtained at avalanche breakdown look more interesting in this respect, as can be seen from Fig 4, which compares the spectral output of the $p^+n^+$

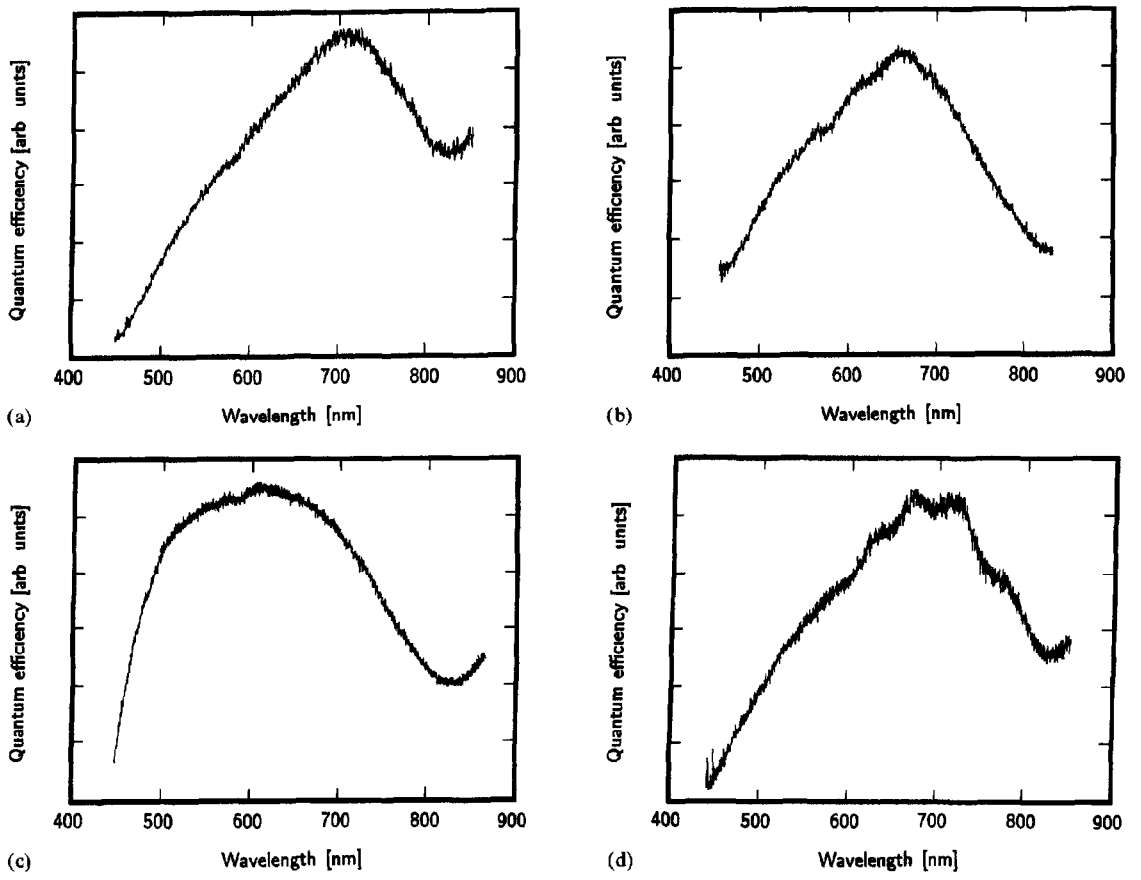


Fig 3 Emission spectra of the CMOS LEDs of Fig 1 operated in avalanche breakdown (a) SACMOS-3 $p^+n^-$ LED, (b) SACMOS-3 $n^+p^-$ LED, (c) SACMOS-3 $p^+n^+$ LED, (d) FORESIGHT $p^+n^-$ LED The spectra are shown in arbitrary units on a linear scale in terms of quantum efficiency per unit wavelength range, i e , number of emitted photons per unit wavelength range

TABLE 1 Characteristics of different LEDs operated in the avalanche breakdown regime Efficiencies relate to conversion of the electrical signal into optical radiation with wavelengths shorter than 850 nm

| Process<br>Junction type | SACMOS-3<br>$p^+n^-$ | SACMOS-3<br>$n^+p^-$ | SACMOS-3<br>$p^+n^+$ | FORESIGHT<br>$p^+n^-$ |
|---|---|---|---|---|
| Typical reverse voltage (V) | 52 0 | 31 2 | 6 5 | 33 2 |
| at reverse current (mA) | 12 | 20 | 100 | 25 |
| Peak wavelength (nm) | 710 | 660 | 610 | 700 |
| Power conversion efficiency | $1\,1 \times 10^{-9}$ | $3\,9 \times 10^{-9}$ | $1\,7 \times 10^{-8}$ | $1\,1 \times 10^{-9}$ |
| Quantum efficiency | $3\,4 \times 10^{-8}$ | $6\,5 \times 10^{-8}$ | $5\,4 \times 10^{-8}$ | $2\,0 \times 10^{-8}$ |

LED with the spectral sensitivity of a $p^-n^-$ diode fabricated with the same process The spectra of all LEDs are quite similar in that they exhibit a pronounced peak between 610 and 710 nm and a rapid decrease towards 800 nm This is in strong contrast to most published spectra of silicon avalanche light sources [7, 10, 11], which show a continuous increase towards the infrared The total quantum efficiencies in the considered spectral range, however, are of the same order of magnitude and the general characteristics of the light emission are very similar to those described in ref 7 In Fig 5 the spectrum of our $p^+n^+$ LED is plotted against some fitted curves found in the literature [6, 7, 11, 12] The spectrum measured by Newman [6]

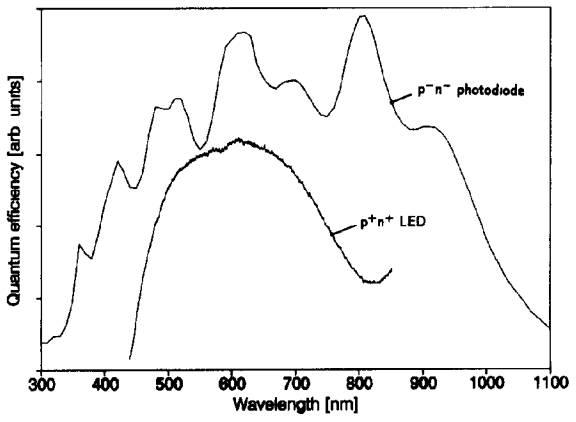


Fig 4 Emission spectrum of the SACMOS-3 $p^+n^+$ LED and spectral response of a $p^-n^-$ photodiode fabricated with the same process

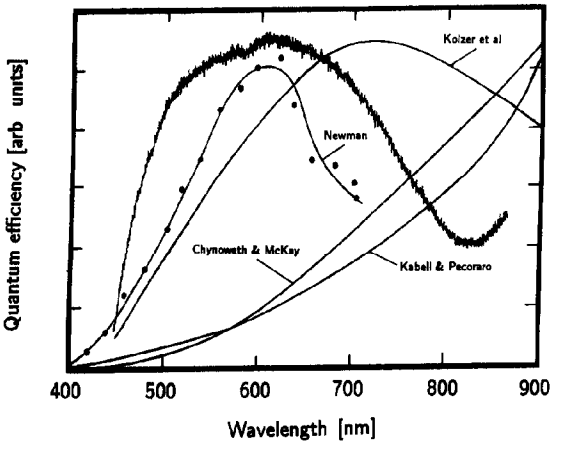


Fig 5 Comparison of different published fitted emission spectra of silicon avalanche LEDs with the one of the SACMOS-3 $p^+n^+$ LED The single data points refer to the spectrum by Newman

has a rather narrow peak centred at around 600 nm, but his data points, which are also shown in Fig 5, are subject to large uncertainties on the long-wavelength side of the peak The position and the width of the peak therefore remain somewhat unclear Recently, Kolzer *et al* [12] also measured a distribution that decreases towards the infrared with a spectral maximum near 700 nm

Visible radiation from our LEDs is only observed where the diode junction reaches the silicon surface If there was any light produced in the vertical region of the junction, a large portion of it would be emitted from the device despite self-absorption in the silicon and reflection at the oxide interface, since the junctions are only about 0 5 μm beneath the surface We conclude that nearly all the light is produced near the edge of the junction close to the surface, which is probably due to the fact that the avalanche breakdown voltage is lower when the junction is not planar Thus self-absorption can probably be neglected

The mechanism causing the light emission has not been identified yet Most older theories [6, 7] suggest that the high-energy end of the spectrum is dominated by phonon-assisted recombination of hot electrons and holes and the lower-energy radiation is produced by intraband transitions of such carriers For both effects the maximum photon energy is limited by the fact that at carrier energies slightly higher than the threshold for ionization by collison, the electron–hole pair production starts to dominate the radiative recombination process This critical energy has been estimated to be around 2 3 eV [13] As the recombination of a high-energy electron with a high-energy hole is very unlikely, it is expected that practically no photons are emitted with energies higher than 3 4 or 2 3 eV for interband or intraband transitions, respectively The minimum photon energy for the recombination process is the band-gap energy of 1 1 eV, whereas intraband transitions have no measurable low-energy limit The superposition of these two effects would imply the occurrence of an inflection point in the spectra somewhere between 1 1 and 2 3 eV, which has not been observed The emission in the infrared was later explained by direct intraband transitions of holes [14] Another theory [15] attributes the entire emission spectrum to bremsstrahlung produced by indirect intraband transitions of hot electrons in the conduction band in the field of charged impurity centres This would give rise to a spectral distribution that increases monotonically with the wavelength In order to explain the visible radiation, an extremely high electron gas temperature of around 5000 K would have to be assumed, however

As our LED spectra exhibit a peak in the visible and a rather low emission between 800 and 850 nm, they are obviously not dominated by bremsstrahlung below 800 nm We may also conclude that the temperature radiation of the crystal lattice is negligible in this range, which is confirmed by the fact that the quantum efficiency and the shape of the spectra are nearly independent of the input current and therefore of temperature This has also been pointed out in previous publications [7, 10, 14] In fact, simple estimations of local lattice temperatures suggest that the increase in the spectral response towards the infrared from around 820 nm, which is observed in most of our spectra, is mainly due to blackbody radiation

It is also conceivable that the presence of nanostructures contributes to the effect, as has been suggested for porous silicon [3, 4, 16] SEM pictures of our devices show that small particles are present on or near the silicon surface They seem to have random shape and

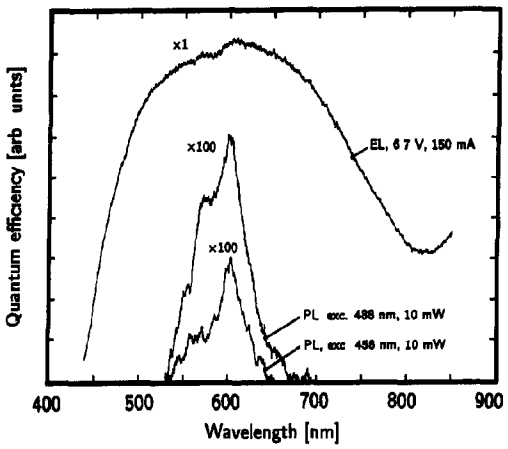


Fig 6 Emission spectrum of the SACMOS-3 $p^+n^+$ LED for electroluminescence (EL) near avalanche breakdown and photoluminescence (PL) at two different excitation wavelengths

size distributions with a diameter range from less than 10 nm (not resolvable by the SEM) to about 100 nm Probably, these are silicon particles formed during the metallization step of the CMOS process, when the deposited aluminium, which is known to contain 0 5% silicon, is etched away

Another possibility is that the effect is not caused by the silicon structure itself, but by other elements or compounds introduced during the various process steps Photoluminescence measurements reveal several peaks which cannot be attributed to silicon In Fig 6 the measured photoluminescence spectra of the $p^+n^+$ diode at two different excitation wavelengths are plotted against its avalanche electroluminescence spectrum The correspondence of the photoluminescence peaks with the fine structure of the LED spectrum suggests that such particles do contribute to some extent to the effect The $p^+n^+$ structure has a high concentration of boron used for p-implantation and phosphorus used for n-implantation at the junction This may segregate boron phosphide (BP), which has an indirect band gap of 2 0 eV and exhibits several photoluminescence peaks in the vicinity of 700 nm [17] The band-gap energy, which is probably higher for small particles than for bulk BP due to quantum-size effects, and these peaks, although they do not seem to correspond to the ones we observed, make BP a possible candidate for electroluminescence in the spectral range of the observed emission peak

The assumption that the electroluminescence of silicon is strongly influenced by the treatment of the chips could explain why the spectra measured by different people show such great discrepancies However, the spectra we measured for two different CMOS processes are in surprisingly good agreement

Further research towards the understanding of the mechanism is under way and will hopefully help us to optimize the LEDs

## 5. Applications

The very low efficiency of the LEDs produced until now limits the optical output power to a few nW For example, the maximum output power measured for the $p^+n^+$ LED was 25 nW, corresponding to an intensity of 1 mW/cm$^2$ The main problems are the high power consumption (2 5 W in our example) and the heat dissipation, which causes the metal interconnects to burn through at the contacts to the silicon at high currents The junctions with more lightly doped layers also require the application of high voltages, but the $p^+n^+$ diode can be operated at CMOS levels

Silicon LEDs have already been used in light pulser devices for the calibration of nuclear event counters, where their rapid turn-on and turn-off times of less than 3 ns have been exploited, and for the recording of digital data on photographic film [11] These devices have a very high reliability and long lifetime Silicon optocouplers and integrated displays have also been proposed [18]

The use of LEDs in integrated optical metrology systems is practical as long as a resonable amount of the emitted light arrives at the detector Typical SACMOS-3 photodiodes can detect optical signals of a few pW, which means that about 0 1% of the emitted light has to arrive at the detector Possible applications include an electronic spirit-level control system and a time-of-flight rangefinder

## 6. Conclusions

We have shown that light-emitting devices can be integrated using industrial CMOS technology and operated at CMOS voltage levels Their emission spectrum is well matched to the response of photodiodes fabricated with the same processes and their efficiencies are of the same order of magnitude as those of devices with optimized doping parameters Thus, single-chip integrated optical metrology systems (photo-ASICs), consisting of light sources, detectors, analog and digital electronics can be produced at low prices and in small quantities on multi-project wafers offered by several silicon foundries in Europe and the USA Investigations are being carried out in our laboratory to understand the physical nature of the effect underlying the light-emission mechanism This may enable us to optimize the devices, improving their efficiency, which, albeit very low in the LEDs produced so far, is already good enough for the first practical applications

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## Biographies

*Jorg Kramer* was born in Zurich There he graduated in physics at the Swiss Federal Institute of Technology (ETH) in 1987 He received an M Sc degree in applied optics from Imperial College of Science and Technology, London, in 1988, and is now working towards a Ph D at the Paul Scherrer Institute in Zurich His current research interests are in optics and optoelectronics

*Peter Seitz* was born in Basel, Switzerland He received his M Sc degree in experimental physics (1980) and his Ph D degree (1984) from the ETH Zurich, working at the Institute for Biomedical Engineering This work was in the field of computed tomography, specializing in room-temperature semiconducting X-ray detectors and the mathematics of image reconstruction from incomplete projections In 1984 he joined Laboratories RCA Ltd in Zurich, where he worked in the optics and image processing group In 1987 he transferred to the reorganized laboratory performing high-technology research as part of the Paul Scherrer Institute, where in 1989 he was appointed head of the newly formed image-sensing group His interests centre around solving problems in applied optics and physics, using novel sensors as well as advanced signal- and image-processing techniques

*Edgar Steigmeier* studied physics at the ETH Zurich, where he received the Ph D degree in 1960 From 1960 to 1962 he worked for Brown Boveri Corporation in Baden, Switzerland on thermoelectric energy conversion In 1962 he joined Laboratories RCA Ltd in Princeton, NJ, USA, performing research on thermoelectric materials and working as a consultant for the RCA fabrication plants In 1964 he transferred to the laboratory in Zurich, where he was mainly concerned with studies on thermal properties of materials and on phase transitions by means of optical spectroscopy and Raman scattering In 1969, 1979 and 1984 he received RCA Awards for his work on the Raman effect, the development of a spectrometer and research on polysilicon for semiconductor devices From 1973 to 1974 he gave invited lectures on solid-state physics at the University of Freiburg, Germany In 1987 he joined the newly formed Paul Scherrer Institute, where he is involved in research on silicon on insulators (SIMOX) for fast devices, epitaxial layers, III–V semiconductors and porous silicon He developed a light-scattering topography system for these materials

*Heinrich Auderset* graduated in mechanics in 1964 From 1964 to 1967 he worked at the Physical Meteorological Observatory in Davos, Switzerland, on problems of global solar radiation standards In 1967 he joined Laboratories RCA Ltd in Zurich He was involved in work on Raman scattering of magnetic semiconductors, ferroelectrics and low-dimensional materials like inorganic and organic conductors, and in the development of an optical scanner for dust and defect detection on semiconductor materials At present he works on materials characterization of silicon and III–V semiconductor wafers by means of Raman scattering and the optical scanner In 1979 Mr Auderset received an RCA

Outstanding Achievement Award for this contribution to the development of the laser scanner

*Bernard Delley* was born in Basel There he graduated in experimental physics and received his Ph D degree in 1979, working on transport properties of liquid metals In the course of this work he developed a contactless method for high-temperature resistivity measurements He was research associate at Northwestern University, IL, USA, from 1979 to 1982, in the electronic structure theory group There he got interested in density functional calculations on molecules and clusters and started work on the dmol program As a scientific collaborator at the University of Neuchâtel, Switzerland, from 1982 to 1986, he was involved in the theory of electron spectroscopy in Kondo compounds From 1986 to 1987 he was scientific staff member of Laboratories RCA Ltd in Zurich and transferred to the Paul Scherrer Institute Zurich in 1987 He is now mainly concerned with the electronic structure of semiconductor materials and devices

*Henry Baltes* received the D Sc degree from ETH Zurich in 1971 In the following years he was on the faculties of the Freie Universitat Berlin, the University of Dusseldorf, the University of Waterloo, Ontario, Canada, and the Ecole Polytechnique Fédérale Lausanne (EPFL) In 1974 he joined Landis & Gyr Zug Corporation, where he became head of the solid-state device laboratory active in microsensor research From 1975 to 1982 he taught optics, solid-state physics and microsensors at EPFL From 1983 to 1988 he held the Henry Marshall Tory Chair at the University of Alberta, Edmonton, Canada, where he directed a research program in microsensors As acting president of the Alberta Microelectronic Centre, he was in charge of the establishment of a CMOS fabrication facility From 1986 to 1988 he also was a director of LSI Logic Corporation of Canada Since 1988 he has been professor of physical electronics at ETH Zurich and head of ETH's Physical Electronics Laboratory active in silicon microsensors In 1991 he joined the Board of Directors of Ascom Microelectronics and was appointed direct of the Swiss Federal Priority Program LESIT

Professor Baltes is an associate editor of *Sensors and Materials* and the *Journal of Micromechanics and Microengineering* He is a member of the IEEE, the Optical Society of America, the Institute of Physics, the Electrochemical Society, the Swiss Information Technology Society, the Swiss Electrotechnical Association, the Swiss Society for Sensor Technology and the Swiss Physical Society