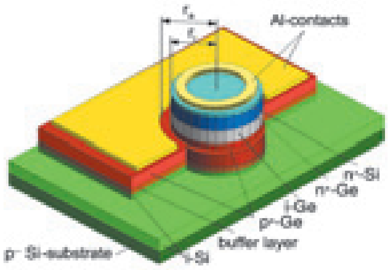
# Silicon-based photodetectors for high-speed integrated optical receivers



One of the main tasks of communication engineering is to provide the transmission of a certain amount of data over a long distance in a short period of time. We all use electrical and wireless data transmission systems day by day but one of the oldest methods to transmit information is using light signals. Simple fires, light houses, a mirror to reflect the sunlight or a torch. The amount of data to be transmitted and also the data rate is rather limited, of course. The real revolution in optical data transmission was caused by the commercial use of optical fibers in the 1980ies.

With the optical fibers it was possible to transmit digital data between continents on commercial transmission lines with data rates from several Mbits/s up to several Gbit/s nowadays. Actually, in laboratory experiments the transmission of more than 10 Tbit/s over a single fiber was demonstrated. A single ISDN phone call requires only 64 kbit/s. The maximum data rate of these systems is mainly limited by the electronic circuits in the transmitter and receiver, not by the fiber itself. Therefore the main interest of the researchers is to develop faster electronic components. On the other hand, the open market forces the researchers to develop cheap components, which is contradictory in a way.

## 1. Silicon and Germanium as detector material

One solution to get fast and cheap devices is to use the well established silicon based technology for integrated circuits and just add the photodetector in the same process. This allows fabricating fully integrated pure Silicon photodetectors in a commercial CMOS process that work at data rates up to some Gbit/s. An example of a 2 GBit/s CMOS-receiver with integrated photodiode and preamplifier designed at the Institut für Elektrische und Optische Nachrichtentechnik (INT) is shown in **(01)**. This receiver can be used in plastic optical fiber (POF) links that work in the visible range or can be integrated e.g. together with a processor core for fast optical memory access.

The optical fiber communication systems operate in the infrared region, mostly at 1.5 µm and in some cases at 1.3 µm. There are so called transmission windows of the fibers with low absorption allowing long distance transmissions. But Silicon photodetectors are able to detect light only in the visible range (wavelength from 0.4 µm to 0.8 µm) up to a wavelength of approximately 0.85 µm. Thus Silicon photodetectors are not suitable for infrared light even though highly desired due to the monolithic integration with complex circuits.

In recent years, the element Germanium was added to pure Silicon to improve significantly the performance of transistors, which are key elements in electronic circuits. The so called SiGe-technology is very fast and more cost-efficient than other technologies used for high-speed circuits, e.g. GaAs or InP. Another advantage of Germanium is the ability to detect light with wavelengths up to 1.6 µm.

Using the compound semiconductor Silicon-Germanium (SiGe) the absorption coefficient in the infrared region rises with higher Germanium contents. Pure Germanium absorbs photons of 850 nm 65 times better than pure Silicon. An overview of the absorption of some common semiconductor materials is shown in **(02)**.

Pure Germanium is well suited for photodetectors in fiber optical communication systems, but there are some restraints in combination with the Silicon technology.

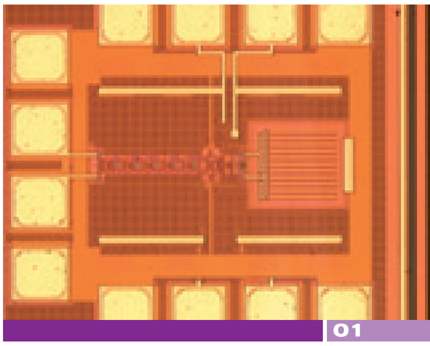
First of all the growth of a Germanium layer on a Silicon substrate is very sophisticated due to the lattice mismatch of about 4 percent. Only thin Germanium layers up to some nanometers grow perfectly but are strained. If the thickness increases, the layers are relaxed but the density of defects and dislocations increases. A modified process, developed at the Institut für Halbleitertechnik (IHT) at the Universität Stuttgart [2], uses low temperature growth to force the defects to arise at the materials interface and not in the Germanium bulk. This was a very important step in order to get good device properties.

The second restraint is the dark current. The basic physical structure of a photodetector device is a pn-diode with an intrinsic absorber material between the p- and n-region. This pin-photodiode is operated in reverse bias, i.e. in an ideal device the current is negligible when there is no light. Actually, in real devices there is a current even when there are no photons – the so called dark current.

One part of the dark current is the diffusion current caused by carriers entering the intrinsic region driven by diffusion. This part is proportional to the square of the intrinsic carrier density of the material which is $2.5{\cdot}10^{13}$ $cm^{-3}$ in Germanium and $1.6{\cdot}10^{10}$ $cm^{-3}$ in Silicon. Thus Germanium photodiodes will have a dark current which is about six orders of magnitude higher than in Silicon.

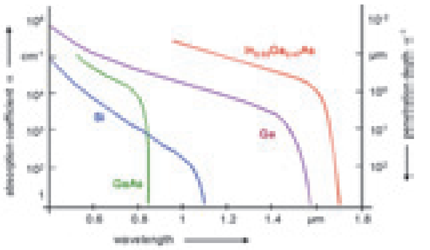
The other part of the dark current is the recombination current which depends on the crystal quality of the material. As mentioned, there is a lattice mismatch between the Silicon and the Germanium crystal introducing defects that feed this recombination current. The recombination current is furthermore proportional to the intrinsic carrier density and to the thickness of the intrinsic absorber region.

In **(03)** the current versus voltage characteristic of a SiGe photodiode designed at the INT and fabricated at the IHT is shown. With increasing reverse voltage the dark current (solid line) raises some orders of magnitude. With illumination at 1298 nm with a power of about 1 mW, the photodiode delivers a photocurrent (dashed line) of about 0.1 mA. The dark current may be completely avoided if the photodiode works at low bias voltages or even without it (zero bias operation). The photodiodes realized by the mentioned cooperation of IHT/INT proved their ability to be operated under zero bias conditions. This was obtained by a proper choice of thickness



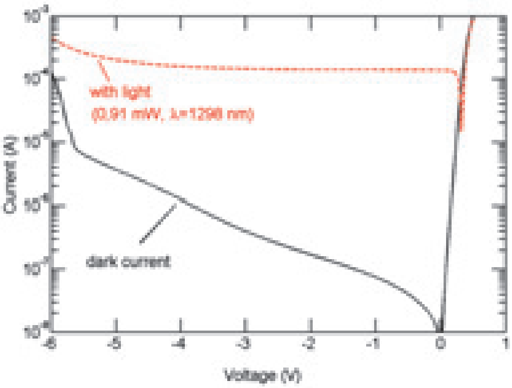
**01**

*Optical CMOS-receiver with fully integrated photodiode for 2 Gbit/s [1].*



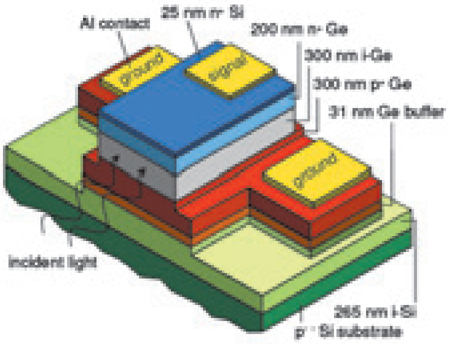
**02**

*Absorption coefficients and penetration depth of common semiconductor materials [3].*



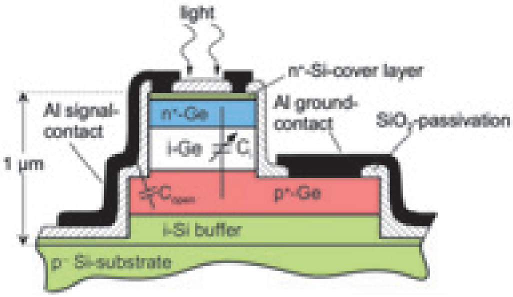
03

*Current versus voltage characteristic of a SiGe photodiode designed at the INT and fabricated at the IHT with (dashed line) and without (solid line) illumination at 1298 nm.*



04

*SiGe waveguide detector [4].*



05

*Cross section of a Ge on Si pin-detector.*

and doping of the device to extend the space charge layer across the absorbing region only by the built-in potential.

The quantum efficiency, i.e. the ratio of generated electrons in respect to the total number of incoming photons, is 23 percent at 850 nm, 16 percent at 1300 nm and 3 percent at 1550 nm. This is, of course, far away from the desired 100 percent. One reason for this is the absence of an antireflection coating, thus approximately one third of the incident light is lost by Fresnel reflection at the detector's surface. Another limitation is the thin absorber region, which is only 300 nm in this device. The longer the wavelength the more light passes trough the intrinsic region, because the absorption coefficient gets smaller and smaller towards the infrared.

## 2. Lateral or vertical structures?

Commonly the photodetector is grown layer by layer on a substrate and the light hits the detector perpendicularly to the surface. This is a vertical structure and the coupling of the light is easy – just by placing a lens or a fiber above the detector. Furthermore, each detector can be tested during the manufacturing process without cutting the wafer. This is an important point for cost reduction during fabrication.

But to overcome the poor sensitivity due to weak absorption in the thin layers of vertical diodes, so called waveguide photodetectors were build. Here the absorber is shaped as a thin, narrow but very long rectangular waveguide. The light travels parallel to the surface through the detector structure and the absorption length can be up to some millimeters, depending on the length of the waveguide.

A waveguide is formed by a region with a high refractive index, which is surrounded by a material with lower refractive index. In a SiGe compound the refractive index increases with increasing Germanium content. This effect can be used to build up waveguide detectors based on the SiGe material. An example of a SiGe waveguide detector is shown in **(04)**.

The light is coupled to a waveguide made of a 300 nm pure Germanium layer. To inject the light into the waveguide a lateral facet has to be created. In order to make the waveguide accessible for fiber coupling, first the waveguide of the diode is cut perpendicularly to the wafer surface with a dice saw. After this first step, the waveguide has a length of several hundred micrometers. Scanning Electron Microscopy (SEM) inspection reveals a considerable roughness of the end facet resulting in high coupling losses. In a second step two tilted cuts perpendicular to the end facet are performed. This cutting procedure yields a triangular, prism shaped cantilever, which is broken off. Now the waveguide has a length of approximately 30 µm and exhibits a smooth end facet.

As the fabrication and the coupling of the light to the detector are difficult, we returned to the vertical structure. A schematic cross section of this is shown in **(05)**.

The basis is a Silicon substrate with a doping concentration as low as possible to avoid high-frequency losses. The detector consists of a 300 nm $p^+$-doped contact layer, a 300 nm absorber layer and a 200 nm $n^+$-doped contact layer. A thin $n^+$-doped Silicon layer improves the top ohmic contact. In terms of speed and time required for growth of the layers, a thin absorber of only a few 100 nm is favorable. Then a Germanium content of close to 100 percent is necessary to get enough sensitivity.

The structure of the complete detector needs only two etching steps. First a mesa is etched out of the $n^+$- and the intrinsic Germanium. The etching depth has to be controlled precisely not to hurt the $p^+$-Ge contact layer. If so, this would thin out the $p^+$-Ge contact layer and increase its resistance leading to a degradation of the detector's RC-time constant.

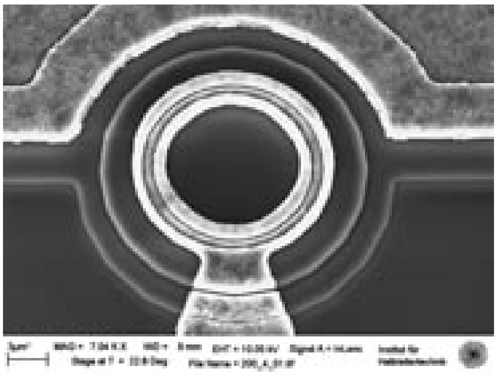
A second etching process structures the $p^+$-contact. It is removed partially to reduce the capacitance $C_{open}$ to the overlap capacitance of the Aluminum signal trace and the $p^+$-Ge contact as shown in **(05)**. By this step of the process, the total device capacitance is reduced close to the intrinsic diode capacitance $C_i$. The pin-structure is isolated by a 500 nm Silica ($SiO_2$) layer with windows opened for the metallic Aluminum contact.

A top view REM picture is shown in **(06)**. The two steps of the mesa etch are apparent as outer circles. The signal contact is a thin Aluminum ring surrounding the active area. The minimum vertical dimensions are determined by the epitaxial growth of the layers, the lateral dimensions are not critical.

For a proper design of the devices, models are needed to simulate the behavior of the devices. An example of a small signal equivalent circuit used to simulate the SiGe pin-photodiode is shown in **(07)**.

The current source $I_{ph}$ represents the conversion of the incoming photons to a photocurrent. The internal capacitance $C_i$ is caused by the space charge region that depends on the applied external voltage. The differential resistance $R_i$ is used to model the dark current in reverse bias. As the dark current depends on the bias voltage, the differential resistance $R_i$ is voltage dependent, too. Those three elements form the inner or intrinsic diode. All other effects caused e.g. by interconnections and contact pads are represented by the series resistance $R_S$, the inductance $L_d$ and the complex impedance $Z_{open}$, respectively.

The device is connected to a measurement system with an input impedance $R_0$ of typically 50 $\Omega$. If too large, the junction capacitance $C_i$ and the impedance $R_0$ are the reason for a severe RC limitation of the bandwidth. Most of all the voltage dependent capacitance $C_i$ has to be as small as possible. The capacitance saturates at high reverse voltages at its minimum, given by the thickness of the intrinsic region and the diode area. On the other hand, high reverse voltages cause large dark currents, as explained before. Thus the saturation voltage of $C_i$ has to be kept as small as possible by a low background doping level of the intrinsic material.



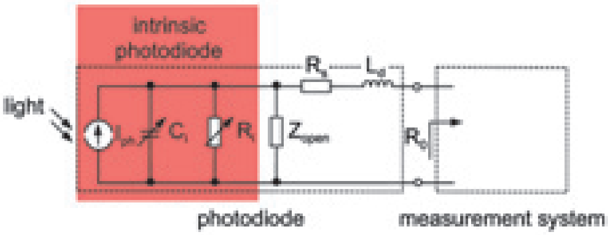
**06**

*REM picture of a Germanium on Silicon pin photodiode.*

Another limitation is the time it takes the carriers to transit the intrinsic region. The minimum time is given by the saturation drift velocity, which is a material constant, and the thickness of the intrinsic region. Taking only the transit time into account, the absorber has to be as thin as possible – but this results in a large capacitance $C_i$. In an optimized structure a compromise of RC-limitation and transit time is found, when the transit time and the RC time constant are equal. The calculation is illustrated in **(08)** using the material parameters of Germanium and three different detector areas.

The RC-bandwidth $f_{RC}$ increases linearly with the thickness of the intrinsic layer, assuming a constant detector area. The transit frequency $f_T$ is independent of the area and decreases with thickness of the intrinsic layer. The intercept point of transit and RC frequency denotes the optimum thickness.

Both frequencies together define the total 3-dB-frequency $f_{3dB}$ of the detector. As can be seen in **(08)**, a high bandwidth can only be obtained with very thin absorber regions and small detector areas. On



**07**

*Small signal equivalent circuit of the SiGe pin-diode.*

SUMMARY

*One of the oldest methods to transmit information is using light signals. But the substantial break trough in optical data transmission was caused by the availability of optical fibers in the 1980ies. Then it was possible to connect countries and even continents by long distance optical transmission lines. The maximum data rate of these systems is mainly limited by the electronic circuits in the transmitter and receiver, not by the fiber itself. Therefore the main interest of researchers is to develop faster electronic components. To be competitive and to open new fields of applications e.g. in multimedia systems in upper class cars the components must be economically priced.*

*Thus it is important to realize sophisticated designs with standard technologies and not standard designs with expensive technologies, whenever it is possible. Unfortunately, most photodetectors suitable for the infrared wavelengths of fiber optical communication links are made of Gallium-Arsenide that requires an expensive technology.*

*In a joint project of the Institut für Halbleitertechnik and the Institut für Elektrische und Optische Nachrichtentechnik, both at Universität Stuttgart, structures and processes for the fabrication of fast photodetectors were developed that combine the well established Silicon-technology with the good infrared absorption properties of Germanium. The realized devices feature a bandwidth of 39 GHz, which is up to now the highest bandwidth reported for such structures.*

## ZUSAMENFASSUNG

*Eine der ältesten Methoden zur Informationsübertragung ist das Senden von Lichtsignalen. Der wirkliche Durchbruch der optischen Datenübertragung kam jedoch erst mit der Verfügbarkeit von Glasfasern in den 1980ern. Damit war es möglich, Länder und sogar Kontinente über optische Weitstreckenverbindungen zu verkabeln. Die maximale Datenrate dieser Systeme ist hauptsächlich durch die elektronischen Schaltkreise im Sender und Empfänger begrenzt, nicht so sehr durch die Faser selbst. Daher liegt das Hauptinteresse der Forscher in der Entwicklung immer schnellerer elektronischer Komponenten. Um wettbewerbsfähig zu bleiben und auch neue Anwendungsgebiete zu eröffnen, wie z.B. Multimedia-Systeme in Oberklasse-Wagen, müssen die Komponenten preiswert sein.*

*Daher ist es wichtig, wann immer möglich ausgeklügelte Entwürfe in Standard-Technologien zu realisieren anstatt in sehr teuren Technologien Standard-Entwürfe umzusetzen. Leider sind die meisten Photodetektoren, die sich für die infraroten Wellenlängen der faseroptischen Kommunikationsverbindungen eignen, aus Gallium-Arsenid gefertigt, was eine teure Technologie erfordert.*

*In einem Verbundprojekt des Instituts für Halbleitertechnik und dem Institut für Elektrische und Optische Nachrichtentechnik, beide Universität Stuttgart, wurden Strukturen und Prozesse zur Herstellung von schnellen Photodetektoren entwickelt, die die etablierte Silizium-Technologie mit den guten Absorptionseigenschaften des Germanium im Infraroten verbinden. Die gefertigten Bauelemente bieten eine Bandbreite von 39 GHz, was der derzeit höchste Wert ist, der berichtet wurde.*

the other hand this results in reduced quantum efficiency and requires tighter tolerances for the alignment of the fiber. The detector shown in **(06)** has a diameter of 10 µm which results in an optimum thickness of 300 nm. The theoretical 3-dB frequency limit is then about 40 GHz.

## 3. State of the art

To get a real device with a bandwidth as close as possible to the theoretical limit, a sophisticated growth process and an optimized design of geometry and layout are necessary.

The main challenges are

- to grow a pure Germanium absorber layer with low defect density and optimum thickness on a Silicon substrate;
- to control the background doping of the intrinsic layer for a low reverse bias voltage;
- to reduce parasitic capacitances by an optimized layout.

**(09)** shows the measured results of the state of the art Germanium on Silicon pin-diode with a 3-dB frequency of 38.9 GHz at a modest reverse bias of -2 V [5]. The diameter of the device is 10 µm. For comparison, the data for devices of 20 µm and 30 µm diameter are also shown.

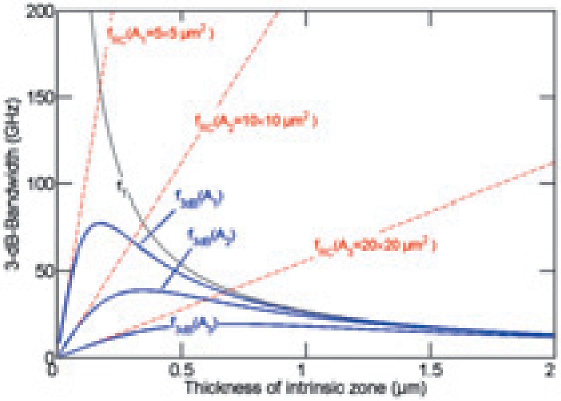
Even as important, high frequency limits (28 GHz) were also obtained with zero bias operation. The slight decrease in 3-dB frequency is caused by a higher internal capacitance.

## 4. The future

Germanium photodiodes monolithically integrated on Silicon substrates feature large bandwidth and a high potential for future optoelectronic systems based on Silicon. They can be used for long distance point to point transmission as well as for parallel data transfer in optical subsystems of computers or even for optical on-chip clock distribution.

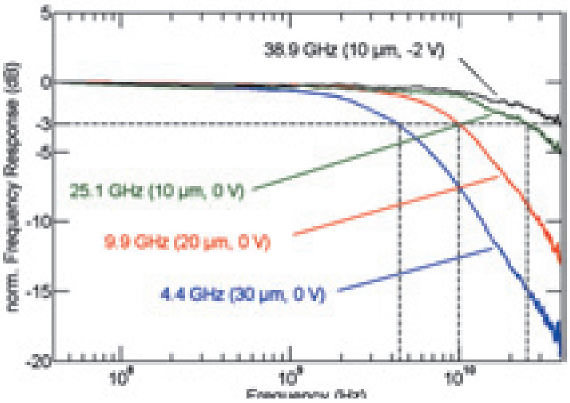
For both fast, i.e. above 40 GHz, and highly efficient Ge-detectors new concepts have to be investigated. Some groups work with resonant structures, where the absorber is embedded between mirrors and the light is traveling several times through this layer. This extends the path, where the photons are absorbed without increasing the thickness of the absorbing layer. The quantum efficiency is several times better but the detector works well only at dedicated wavelengths because of the resonant structure.

Another idea is to combine the easy vertical coupling with the high efficiency of the waveguide detector by sophisticated coupling structures. The vertically incoming light perpendicular to the wafer's surface has to be forced to couple into a waveguide parallel to the wafer's surface. An approach for such a coupling structure



08

*Theoretical 3-dB-frequency of an ideal pin photodetector.*



09

*Measured frequency response of Germanium on Silicon pin-diodes with different diameters.*

could be e.g. an integrated diffraction grating, which is investigated currently.

## 5. Acknowledgements

The presented article summarizes the results of a joint project of the Institut für Halbleitertechnik (IHT) and the Institut für Elektrische und Optische Nachrichtentechnik (INT), both at Universität Stuttgart, in the field of fast SiGe-photodetectors.

The vertical pin detector with a pure Germanium absorber on a Silicon substrate was designed and characterized at the INT; the processing was developed and performed by the IHT.

The authors would like to thank Wolfgang Vogel and Markus Grözing from INT and Michael Öhme, Gerd Wöhl and Klaus D. Matthies from IHT for their support and their work.

*Manfred Berroth*
*Erich Kasper*
*Michael Jutzi*

## References

1 M. Jutzi, M. Grözing, E. Gaugler, W. Mazioschek, M. Berroth, 2-Gb/s CMOS Optical Integrated Receiver With a Spatially Modulated Photodetector, IEEE Photonics Technology Letters, Vol. 17, No. 6, 2005, pp. 1268–1270.

2 M. Bauer, C. Schöllhorn, K. Lyutovich, E. Kasper, M. Jutzi, M. Berroth, “High Ge Content Photodetectors on Thin SiGe Buffers”, Mater. Sci. Eng. B, Vol. 89, 2002, pp. 77–83.

3 See e.g. S. M. Sze, Semiconductor Devices Physics and Technology, John Wiley & Sons, 2001.

4 M. Jutzi, M. Berroth, G. Wöhl, M. Oehme, V. Stefani, E. Kasper, “Ge-on-Si Pin-Photodiodes for Vertical and In-Plane Detection of 1300 to 1580 nm Light”, 34th European Solid-State Device Research Conference, September 20–24, 2004, Leuven, Belgium, pp. 345–348.

5 M. Jutzi, M. Berroth, G. Wöhl, M. Oehme, E. Kasper, “Ge-on-Si Vertical Incidence Photodiodes with 39 GHz Bandwidth”, IEEE Photonics Technology Letters, Vol. 17, No. 7, 2005, pp. 1510–1512.

zurück zum Inhalt

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