Germanium-on-Insulator Photodetectors

S. J. Koester,* G. Dehlinger, J. D. Schaub, J. O. Chu, Q. C. Ouyang, and A. Grill
IBM T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598
**Ph: (914) 945-2189, FAX: (914) 945-4581, Email: skoester@us.ibm.com*

Abstract

This paper provides an overview of IBM's recent results on Ge-on-insulator (GOI) photodetector technology and describes their suitability for use in so-called "in-the-box" massively-parallel optical interconnects.

Motivation

Currently, today's high-performance servers utilize copper for local (chip-to-chip, board-to-board and rack-to-rack) interconnects. However, as bandwidth requirements continue to increase, there will be a greater push to incorporate so-called "in-the-box" optical solutions for interconnects. The reason is that as data rates increase to several Gbit/sec per channel, traditional copper links cannot transmit more than a few meters. Furthermore, the edge connector density is restricted using copper interconnects, limiting the overall system throughput. Not only would highly-parallel optical data links offer superior performance in terms of bandwidth-length product, but, as data rates scale, they should also improve the overall interconnect density, power dissipation and synchronization. The transition to optical interconnects is expected to occur first at the rack-to-rack level. However, as bandwidth requirements continue to increase, optical solutions will also be needed for board-to-board and finally chip-to-chip interconnects, as shown schematically in Fig. 1.

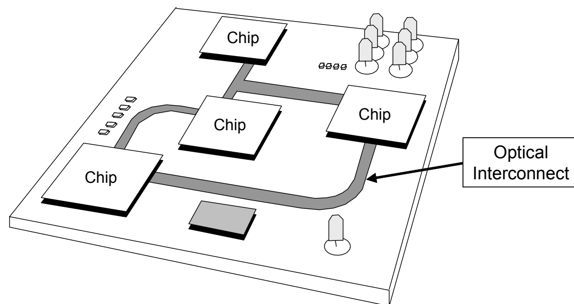

Fig.1. Conceptual diagram of chip-to-chip opto-electronic interconnects.

Unfortunately, conventional fiber-optic technology is generally too costly for utilization in server-based optical interconnects. For instance, systems designed for data transfer over long distances (> 1 km) typically utilize III-V-based emitters and detectors, and tend to operate at 1.55 μm using expensive single-mode fiber. Even technology for local communications systems that operate at 850 nm and utilize low-cost multi-mode fiber, are likely cost prohibitive, because they still require GaAs lasers and detectors. When combined with Si-based electronics, III-V-based systems also suffer performance degradation due to packaging parasitics and crosstalk associated with wire-bond leads.

Therefore, the ideal solution for low-cost high-performance optical interconnects would be a Si-based integrated approach, which offers the cost advantage of high-volume silicon manufacturing. Furthermore, an integrated solution could eliminate the parasitics and noise associated with hybrid packaging technology.

Despite these potential advantages, however, the long absorption length in silicon (~ 20 μm), makes it difficult to overcome the fundamental speed / responsivity trade-offs associated with photodetector technology. On the detector side, IBM's deep trench detector design offers one method of overcoming this limitation, but the extendibility of this technique to higher speeds is limited [1]. Si resonant cavity photodetectors can also provide high performance, but involve significant process complexity [2].

In this paper, we describe a photodetector design based upon a Ge-on-insulator design that offers nearly all of the desirable performance features needed for integrated optical receivers, while at the same time maintaining the potential for low-cost integration with mainstream Si-based technology.

Benefits of Ge

The concept of adding Ge to improve Si photodetector responsivity and speed is not new [3]-[4]. However, SiGe alloys do not substantially increase the absorption coefficient or increase the cutoff wavelength until very high Ge concentrations are reached. Therefore, as shown in Fig. 2, the use of pure Ge detectors is preferred to provide the maximum absorption coefficient improvement and cutoff wavelength increase compared to Si.

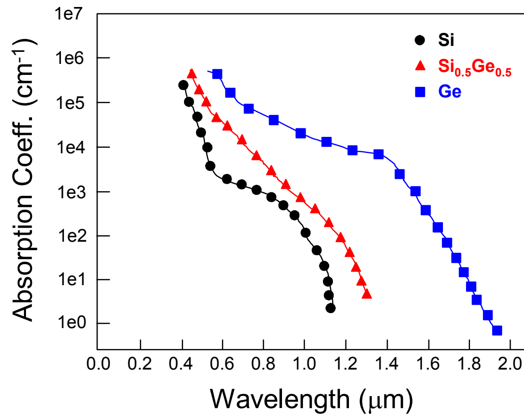

Fig. 2. Plot of absorption coefficient vs. wavelength for Si, $Si_{0.5}Ge_{0.5}$ and Ge.

The use of Ge detectors on Si offers a significant integration challenge due to the 4% lattice mismatch between Si and Ge. Ge photodiodes based on graded buffer-layer technology were demonstrated in [5], but the thickness of graded buffers tends to make CMOS integration difficult. More recently several groups have utilized a direct Ge-on-Si approach [6], because much thinner Ge layers can be utilized, and reasonable defect densities can still be obtained, particularly after post-growth annealing [7]. Such devices can offer good performance at 1.3 μm and 1.55 μm, but at short wavelengths, the device performance is degraded significantly due to the underlying Si absorption [8].

GOI photodetectors

In order to address the deficiencies of previous Ge photodetector designs, we have developed the Ge-on-insulator (GOI) detector design shown in Fig. 3 [9]. This technology utilizes a pure Ge absorbing layer grown directly on a thin SOI substrate. The SOI serves the dual purpose of preventing carriers generated in the substrate from being collected by the contact electrodes, as well as limiting the amount of Si available for interdiffusion with Ge. This later benefit is particularly critical given the fact that substantial degradation of the responsivity can occur after post-growth annealing due to the sensitive dependence of the absorption coefficient on the Si concentration in dilute GeSi alloys.

The electrodes are arranged in a lateral p-i-n geometry, which minimizes the device capacitance and enables planar processing. Due to the high absorption coefficient, the Ge absorbing layer can be made very thin (~ 400 nm), and thus allow small electrode spacings. In our devices we have utilized finger spacings, S, as small as 0.4 μm, roughly equal to the absorbing layer thickness. In order to reduce the series resistance of the contact fingers, the electrodes are strapped with aluminum. The device area was typically 10 x 10 μm^2, though larger devices have also investigated. In the following sections we describe the performance features that make these detectors well suited for optical interconnect applications.

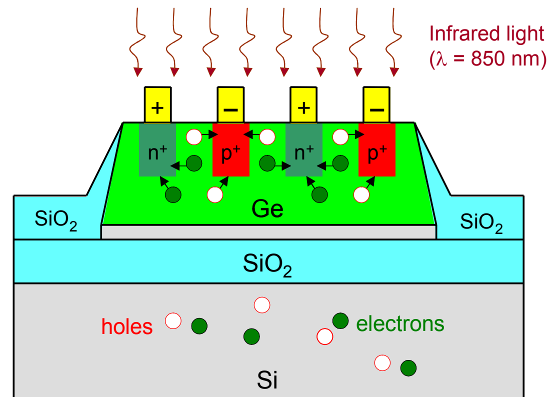

Fig. 3. Schematic cross-sectional diagram of lateral GOI photodetector design.

Speed / bias

As shown in Fig. 4, we have demonstrated devices with S = 0.4 μm that have bandwidths as high as 29 GHz at a bias voltage, V_b, of -1 V. Furthermore, devices with finger spacings as large as S = 0.8 μm achieved bandwidths greater than 20 GHz at the same bias. Even at zero bias, the smallest devices displayed bandwidths of 25 GHz, a result of the finger spacing being roughly equal to the depletion width between the

n+ electrodes and the slightly p-type Ge absorbing layer. The excellent performance at low bias is extremely important for integrated applications, as it allows the photoreceiver amplifier to operate on a single supply.

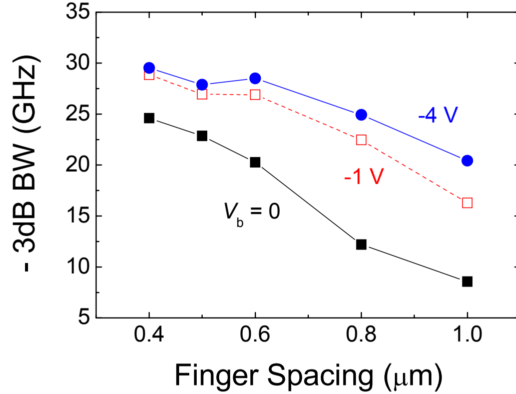

Fig. 4. Plot of GOI photodetector bandwidth vs. finger spacing for 10 x 10 μm^2 detectors at various bias voltages.

Efficiency

As expected, the photoresponse exhibited resonance peaks due to the reflection caused by the buried oxide. Devices with S = 1.3 μm had an external quantum efficiency, QE, of 52%, where the resonance peaked at λ = 895 nm, and QE = 38% at λ = 850 nm. Devices with smaller finger spacings had slightly lower QE values due to increased shadowing from the metal gate fingers. However, these devices did not have an anti-reflection coating (ARC). Without any other modifications to the device design, the QE value is expected to increase to 78% with the addition of a Si_3N_4 anti-reflection coating (ARC). Optimization of the buried oxide and ARC thicknesses are expected to further improve the responsivity. The extra responsivity could also be traded off to decrease the thickness of the absorbing layer, thereby allowing even closer finger spacings and high-speed operation.

Dark current

One of the main concerns with Ge photodetectors is dark current, not only due to the low band gap, but also the high defect density associated with the direct Ge on Si growth. However, due to the ability to operate at low voltage, we have found that GOI detectors can maintain acceptable dark current values. For instance, 10 x 10 μm^2 detectors displayed a dark current of ~ 10 nA at V_b = -0.5 V, a value that was virtually independent of finger spacing down to S = 0.4 μm. The extent to which the dark current can be further decreased by using surface passivation or reducing defects remains an important topic for further investigation.

Overall performance assessment

An overall performance assessment of the GOI photodetectors is shown in Table 1. This plot shows the simultaneously achieved values of bandwidth, quantum efficiency at λ = 850 nm, bias voltage and dark current. The quantum efficiency at λ = 895 nm is also shown. The table clearly shows that GOI photodetectors can offer nearly all of the desirable performance features needed for integrated optical receivers.

Table 1. Simultaneous performance values for 10 x 10 μm^2 GOI photodetectors.

S (μm)	BW (GHz)	QE (λ=850nm)	QE (λ=895nm)	V_{bias} (V)	I_{dark} (nA)
0.4	27	31%	43%	0.5	8
0.6	27	34%	47%	1.0	24

Summary and Outlook

We have demonstrated the performance benefits of GOI photodetector technology for future applications. In our presentation we will also describe future challenges and opportunities for the use of GOI technology in optoelectronic interconnects, and describe our outlook for other applications of group-IV photonics in high-performance computing systems.

References

[1] M. Yang, *et al.*, IEEE Elec. Dev. Lett. **23**, 395 (2002).
[2] J. D. Schaub, *et al.*, IEEE Phot. Tech. Lett. **11**, 1647 (1999).
[3] X. Shao, *et al.*, Appl. Phys. Lett. **71**, 1860, (1998).
[4] S. J. Koester, *et al.*, Device Research Conference, 1998.
[5] S. B. Samavedam, *et al.*, Appl. Phys. Lett. **73**, 2125, 1998.
[6] L. Colace, *et al.*, IEEE J. Quant. Electron. **35**, 1843 (1999).
[7] H.-C. Luan, *et al.*, Appl. Phys. Lett. **75**, 2909 (1999).
[8] G. Dehlinger, *et al.*, ISTDM, 2003.
[9] S. J. Koester, *et al.*, Device Research Conference, 2004.