Infrared Photodetectors on a Silicon Chip

As is well known, the celebrated silicon technology has not been able to produce an on-chip infrared photodetector for long-wavelength fiber-optics communications. The obvious difficulty lies in the fact that silicon bandgap E_G is wider than the photon energy in the range of silica-fiber transparency ($\lambda = 1.3 - 1.55\ \mu$m). Attempts have been made to overcome this difficulty by using Schottky-barrier structures with photoexcitation of carriers from the metal (or silicide) into silicon. The threshold for such a photoeffect is determined by the Schottky-barrier height and can easily match the required infrared range; however, the quantum efficiency of absorption in such structures is usually low. *Lab 5211 does not recommend the use of Schottky-barrier detectors for the 6.8 GHz lightwave system.*

So far, the only practical way of employing silicon technology for fiber-optics communications has been to combine Si integrated circuits with Ge or InGaAs-on-InP detectors on a separate chip. The use of separate chips introduces additional parasitics of the interconnection and consequently leads to poorer noise performance [1]. For example, an addition of 0.2 pF of stray capacitance to a 0.2 pF detector will degrade the noise performance by 3 dB. *Lab 5211 is willing to explore the possibility of flip-chip bonding of a detector to a silicon substrate in order to reduce the interconnect capacitance*; however relying entirely on the development of the flip-chip approach would probably introduce too much risk for the 6.8 GHz project.

A different approach to this problem is based on growing single-crystal germanium *pin* junction on a silicon substrate. Molecular beam epitaxy (MBE) grown diodes have been reported [2], which had an absorption spectrum similar to that in bulk germanium (Fig. 1) with a quantum efficiency $\eta \approx 40\%$ at $\lambda = 1.3\,\mu$m. However, the devices suffered from a relatively high reverse-bias parasitic leakage at room temperature. This leakage resulted from threading dislocations originating at the Ge/Si interface due to a large lattice mismatch and propagating through the germanium *pin* junction. In the subsequent work [3] the dislocation density was reduced by a novel MBE trick called the "glitch grading", which consists in inserting a Si_xGe_{1-x}/Ge superlattice in the epitaxially grown germanium film (Fig. 2). It turns out that dislocations tend to be trapped in the strained superlattice region and do not propagate up into the working diode region (the region where photogenerated carriers are separated by the electric field). Ultimately, one should be able to produce on a silicon substrate Ge or even InGaAs layers comparable in quality to bulk samples. In this approach, no use is made of the electronic properties of the heterointerface, nor of the Si substrate itself. The latter merely serves as a carrier vehicle for an incommensurate growth of a useful single-crystal foreign semiconductor. *Lab 5211 recommends this approach provided the loss budget does not indicate that avalanche gain is necessary in the detector.*

However, there is one property of silicon, which is very attractive for use in fiber-optics communications and whose utilization requires *commensurate* epitaxy. Silicon is an ideal material for avalanche multiplication of photogenerated signals. Neither Ge nor InGaAs are ideal avalanche photodetector (APD) materials from the point of view of the so-called *excess noise factor* F, which describes the stochastic nature of avalanche multiplication. The F factor generally depends on the avalanche gain M and the ratio of the impact ionization coefficients $K = \alpha_n/\alpha_p$ for electron and holes. If $K \approx 1$ then $F \approx M$ and the total noise power scales $\propto M^3$. Such is the situation for Ge with $\alpha_p/\alpha_n \lesssim 2$ and InGaAs, where $\alpha_n/\alpha_p \lesssim 2$. On the other hand, if $K \gg 1$ or $K \ll 1$, then $F \approx 2$ even for $M \gg 1$, provided avalanche is initiated by the type of carrier with higher α. It is well established that in Si at not too high electric fields ($\lesssim 3 \times 10^5$ V/cm) the electron ionization coefficient is substantially greater than the hole ionization coefficient. Thus, properly designed Si APD's can have the noise performance near the theoretical minimum. At present, there are commercially available silicon devices with $K \approx 20 - 100$ (of course, these APD's do not operate in the range of interest for fiber-optical communications). It would be very attractive to implement a heterostructure device with *separate* absorption and multiplication regions (SAM APD), in which electrons photogenerated in a Ge or InGaAs layer would subsequently avalanche in Si.

A novel infrared photodetector structure was recently proposed [4], which utilizes the silicon advantage. It represents a *waveguide* in which the core is a strained-layer Ge_xSi_{1-x}/Si superlattice (SLS) sandwiched between Si layers of a lower refractive index (Fig. 3). Absorption of infrared radiation occurs in the core region due to interband electron transitions, and photogenerated carriers are collected in one of the Si cladding layers. Due to the recently discovered effect of bandgap narrowing by the strain in $Ge_x Si_{1-x}$ alloy layers the fundamental absorption threshold of the SLS is shifted to longer wavelengths, so that the detector can be operated in the range of silica-fiber transparency. If the alloy layers are sufficiently thin, the SLS can be grown by MBE without nucleating dislocations. Experimentally, such structures were recently manufactured and tested. The first SLS waveguide *pin* diodes [5] showed an internal quantum efficiency of 40% at $\lambda = 1.3\,\mu$m and a frequency bandwidth of close to 1 GHz. The first APD structure [6] showed an avalanche gain as high as $M = 50$ and a quantum efficiency of 100% at $M = 10$. Note that the wave-guide detector quantum efficiency grows with the optical path length, *without degrading the speed of response*. The waveguide-detector approach is entirely compatible with the Si integrated circuit technology.

The design of a SAM APD waveguide structure, in which low-noise avalanche multiplication occurs in one of the Si cladding layers, should be guided by the following principles (Fig. 4): *i*) since $K \equiv \alpha_n/\alpha_p \gg 1$ in Si, the multiplication should be initiated by electrons rather than holes; *ii*) since K decreases sharply when the electric field much exceeds the ionization threshold, E_i, the field in the avalanche layer should be near the threshold, $E \gtrsim E_i \approx 3\times10^5$ V/cm, and the thickness of that layer should be well above $\alpha_n^{-1}(E_i) \approx 0.5\,\mu$m; *iii*) the field in the SLS layers should not exceed $\sim 10^5$ V/cm, the ionization threshold in Ge. A possible waveguide APD structure contains an undoped Si avalanche layer of thickness $d \gtrsim 2\,\mu$m separated from the SLS by a thin ($\Delta \lesssim 10^{-6}$ cm) p-type Si layer. In the operating regime, the Δ layer must be depleted by an applied reverse bias. The total surface density of charge in this layer should, therefore, be of order $\varepsilon E_i \approx 2\times10^{12}\,e/\mathrm{cm}^2$. This will achieve the desirable hi-lo field separation of the absorption and multiplication layers and result in a low-noise SAM APD structure.

It should be noted that a new scheme was recently proposed [7], which achieves low-noise multiplication of optical signals by producing avalanching in a *finite medium* with only a few ionizing collisions per traversal of the primary carrier. This results in a lower uncertainty in the gain process, giving $F \approx 2$ even for $M \gg 1$ – without requiring that $K \gg 1$ or $K \ll 1$. Initial evidence of this effect has been observed in supershot noise behavior of substrate current in submicron NMOS FET channels. The new scheme gives a wider choice of materials for ultra-low noise avalanche multiplication. Implementation of this scheme certainly requires high-resolution crystal-growth techniques, such as the MBE.

Development of Si-based detectors for optical communications represents one of the most practical applications of silicon MBE research. It offers the possibility of fabricating a complete receiver system for long-wavelength fiber-optics communications on a silicon chip. *Lab 5211 recommends the heteroepitaxial approach as the prefferred backup to the more conventional approaches of using a detector that is separated from the silicon integrated circuit*. This development fits well our research strategy for the next 4-5 years. Lab 5211 is in the process of ordering a comprehensive MBE system which would be capable of the heteroepitaxial growth of Ge and other optically active semiconductor layers on 4’’ wafers – a necessary requirement to be compatible with our fine-line facility. Delivery of this system is anticipated in the 4th quarter of 1987, so that first results can be expected in 1988. We stand a good chance to succeed in producing an integrated receiver system for the 6.8 GHz lightwave project.

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FIGURE CAPTIONS

Fig. 1: Photoresponse spectra of a Ge *pin* diode epitaxially grown on a silicon substate [2] .

Fig. 2: Schematic illustration of the composition of epitaxial layers in Ge/Si infrared photodetectors. a) The original structure [2]. b) Glitch-graded structure [3].

Fig. 3: Schematic illustration of strained $Ge_x Si_{1-x}$ layer waveguide detectors [4]: a) Single-layer core; b) SLS core.

Fig. 4: A waveguide APD structure and the electric field profile [4].