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Waveguide Infrared Photodetectors on a Silicon Chip

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***Abstract*—A novel infrared (IR) photodetector structure is discussed. 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. Absorption of infrared radiation occurs in the core region due to interband electron transitions, and photogenerated carriers are collected in the Si cladding layers. Due to the recently discovered effect of bandgap narrowing by the strain in 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, 1.3–1.55 μm. The optimum SLS composition and thickness have been estimated from the known material properties and waveguide theory. The detector quantum efficiency grows with the optical path length, remaining consistent with the requirements of high-speed fiber-optical communications. A major advantage of the proposed structure is the possibility of obtaining avalanche gain in the silicon cladding. First experimental results have demonstrated the validity of the concept.**

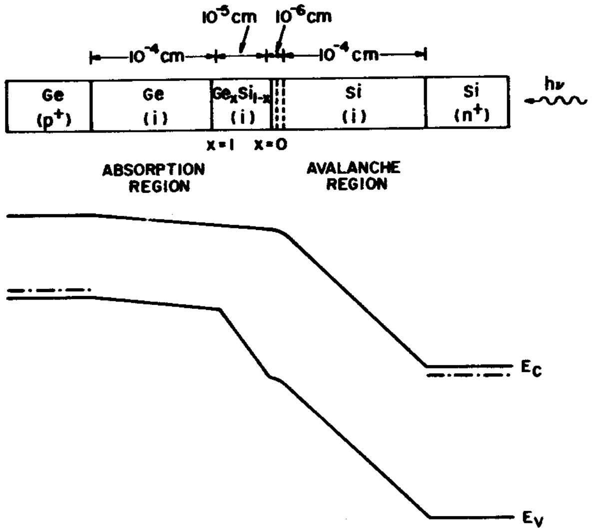

Fig. 1. A possible Ge/Si high-low SAM APD structure (F. Capasso, A. Kastalsky, and S. Luryi, 1983 unpublished) with separate absorption and multiplication regions and high-low electric field profile. Its implementation requires further improvement in the quality of the interfacial germanium layers. Large number of misfit defects, resulting in a high parasitic dark current, may be very difficult to avoid.

RECENT publications [1], [2] have demonstrated the feasibility of fabricating photodetectors for long wavelength fiber-optics communications on a silicon chip. The approach used in those works was to grow single-crystal germanium p-i-n diodes on a silicon substrate. The infrared (IR) active *i*-Ge region was separated from the Ge/Si interface by a thick buffer layer, which made the detector performance insensitive to the presence of material defects at the interface. Ultimately, one may be able to produce in this way a Ge avalanche photodetector (APD) structure—on a silicon chip and entirely compatible with the Si VLSI technology.

One should realize, however, that Ge is not an ideal APD material due to its low value of the ratio of the ionization coefficients for holes and electrons, viz. $\alpha_p/\alpha_n < 2$, which results in a large excess noise factor [3]. In contrast, with $\alpha_n/\alpha_p \gg 1$ (between 5 and 500, depending on the electric field), silicon has a noise performance near the theoretical minimum [3]. It would be ideal to combine absorption in Ge with avalanching in Si, and implement a structure analogous to the well-known InP/$Ga_{0.47}In_{0.53}As$ SAM APD [4]. An example of such a structure is shown in Fig. 1. It contains a depleted layer of acceptors (charge sheet) built in silicon in the vicinity of the Ge interface, whose purpose is to separate the low-field region in the optically active Ge layer from a high-field Si layer where avalanche multiplication occurs. Similar SAM APD structures with hi-lo electric field profiles, produced by a charge-sheet insertion, have been successfully fabricated in III-V compound semiconductors [5]; however, the implementation with Ge/Si heterojunctions requires far better material quality in the interfacial layers than that presently available with any crystal growth technique.

On the other hand, it has been recently established [6] that thin Ge_xSi_{1-x} alloy layers can be grown commensurately (i.e., without dislocations) on a silicon substrate and capped by another silicon layer. The maximum thickness h_c of the alloy layer depends on x, decreasing with the increasing Ge content. People and Bean [7] have calculated $h_c(x)$ on the assumption that the film grows initially without dislocations, which are then generated at the interface, as the strain energy density per unit area of the film exceeds the areal energy density associated with an isolated dislocation. Their result, which implicitly gives $h_c(x)$ in [Å] by the equation

$$x^2 h_c = 13.3 \ \ln\ (h_c/4) \tag{1}$$

is in an excellent agreement with the empirical data. Raman scattering studies [6] have shown that most of the strain in such structures resides in the alloy layer, with Si cladding layers being nearly unstrained. A second Ge_xSi_{1-x} layer can then be grown on the Si cap layer (provided the latter is 2–3 times thicker than the alloy layer), and the sequence can be repeated many times without a noticeable incommensurate growth (as many as 100 periods have been reported [6]). The maximum total thickness of such strained layer superlattices (SLS) can be

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estimated from the semi-empirical rule [8] that the stability of the SLS against the formation of dislocations is equivalent to that of a single alloy layer of same thickness but average Ge content. This rule can be represented by the following expression:

$$h_{\rm SLS}^{\max}(x,\ r,\ T) \approx h_c(xr) \tag{2}$$

where $r \equiv h/T$ is the ratio of the thickness of the alloy layer to the superlattice period (i.e., the "duty cycle" of the superlattice), and $h_{\rm SLS}$ is the total superlattice thickness. Note that $h_{\rm SLS}^{\max} \neq f(T)$, which means that a coarse superlattice with few periods will be as stable as a fine superlattice with many periods, provided they have the same total thickness and the same values of x and r.

It would be very attractive to use the SLS for an IR photodetector—but one has to find a way to circumvent the necessarily low absorption coefficient of a $\rm Ge_xSi_{1-x}$ alloy at wavelengths of interest for fiber-optics communications. An important finding in this regard is the theoretical calculation of People [9] who considered the bandgap narrowing in strained $\rm Ge_xSi_{1-x}$ alloys grown on Si (100) substrates, and found that the gap is substantially reduced in comparison with the unstrained alloy. Lang *et al.* [10] have measured the fundamental absorption threshold in the $\rm Ge_xSi_{1-x}$/Si SLS as a function of the Ge content in the alloy layers and found a good agreement with the theoretical predictions [9]. At $x = 0.6$ the bandgap E_g is narrower than that of pure unstrained Ge, and for $x \gtrsim 0.5$ one has $E_g \lesssim 0.8$ eV. The absorption edge is thus brought down by the strain to below the photon energy at wavelengths of silica-fiber transparency ($\lambda = 1.3$–$1.5\ \mu$m).

However, inasmuch as the $\rm Ge_xSi_{1-x}$ alloy remains an indirect-gap semiconductor at all values of x, one can expect a low absorption coefficient $\alpha \lesssim 10^2\ \rm cm^{-1}$, even at photon energies above the fundamental threshold. An efficient detector would, therefore, require an optical path length of order 100 μm or greater. This requirement appears to rule out the conventional detector designs in which photogenerated carriers travel along the direction of the propagation of light. Indeed, even if one made a 100-μm-thick SLS active layer, with p and n contacts at the top and the bottom, the response time of such a detector would be limited by the time of carrier drift across the SLS—which would be in a nanosecond range, i.e., too slow.

In order to utilize the remarkable properties of a $\rm Ge_xSi_{1-x}$/Si SLS, it is thus imperative to design a detector structure in which the direction of carrier propagation is normal to that of light. It is conceivable to use a thick planar SLS structure with laterally defined n and p contacts spaced one or several micrometers apart, so that carriers generated by incident radiation perpendicular to the surface will then drift laterally over a relatively short distance to the contacts. Such a design, however, appears impractical. In our view, a much better alternative is to use lateral propagation of light and vertical carrier drift. An important advantage in this design is the possibility of using the natural waveguiding property of Si-$\rm Ge_xSi_{1-x}$-Si heterostructures.

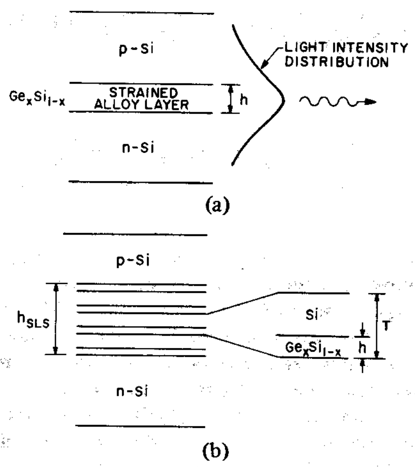

Fig. 2. Schematic illustration of strained $\rm Ge_xSi_{1-x}$ layer waveguide detectors. (a) Single-layer core. (b) SLS core.

Consider first a waveguide-detector structure in which the core represents a single alloy layer, Fig. 2(a). We assume that the Ge content in this layer is $x > 0.5$, and that the absorption coefficient at wavelengths of interest is $\alpha \approx 10^2\ \rm cm^{-1}$ (as indicated by our preliminary results [11] at $\lambda = 1.3\ \mu$m). To be in the range of commensurate growth, the alloy thickness h must be less than the critical $h_c(0.5) = 100$ Å. To a good approximation, the fraction Γ of the integrated intensity of the light wave which falls within the absorbing core, is given by [12]

$$\Gamma = 2\pi^2 \left(\frac{h}{\lambda}\right)^2 (n_{\rm core}^2 - n_{\rm clad}^2). \tag{3}$$

The refractive index of a $\rm Ge_xSi_{1-x}$ alloy is approximately given by a linear interpolation

$$n(x) \approx n_{\rm Si} + x(n_{\rm Ge} - n_{\rm Si}) = 3.45 + 0.55x. \tag{4}$$

For $x = 0.5$, $h = 100$ Å, and $\lambda = 1.3\ \mu$m we thus find $\Gamma = 2.3 \times 10^{-3}$. The effective absorption coefficient of such a waveguide, $\alpha_{\rm eff} = \alpha\Gamma \sim 0.2\ \rm cm^{-1}$, is too low for a practical use (a detector would have to be several centimeters long and even the speed of light is not fast enough over such distances).

The use of a superlattice is thus imperative. Consider the structure illustrated in Fig. 2(b). Ignoring in first approximation the influence of strain on the dielectric constant, we can estimate the refractive index of an SLS as an average of $n^2(x)$ and $n_{\rm Si}^2$ over one period:

$$n_{\rm SLS}^2 \approx \frac{h}{T} n^2(x) + \frac{T-h}{T} n_{\rm Si}^2 = n_{\rm Si}^2 + rx(3.8 + 0.3x). \tag{5}$$

The effective absorption coefficient of an SLS core is given by $\alpha_{\rm eff} = r\Gamma\alpha$, and substituting (5) into (3) one has

$$\alpha_{\rm eff} = 2\alpha(\pi/\lambda)^2 x(3.8 + 0.3x)[rh_{\rm SLS}]^2. \tag{6}$$

In a practical device, the value of x will be determined by the need to absorb at a specific λ, and hence for a fixed r one maximizes $\alpha_{\rm eff}$ by pushing $h_{\rm SLS}$ to its limit given by (2), that is $h_{\rm SLS}^{\max}(x,\ r) = h_c(xr)$. As a function of r, therefore, $\alpha_{\rm eff}$ is maximized together with the function $\phi \equiv zh_c(z)$, where $z =$

xr. With the help of (1) this function can be differentiated, yielding the result that ϕ is a monotonically decreasing function of z for all $z < 1$. One can reach the same conclusion from considering the experimental data [6], which clearly show that $h_c(z)$ decreases faster than $1/z$. Thus we arrive at the result that α_{eff} is maximized by smaller r, which for $h_{\text{SLS}} = h_{\text{SLS}}^{\max}$ implies maximizing the superlattice width.

This result is obtained with the approximation (3) for Γ. Of course, at very small r (and hence large h_{SLS}) the validity of (3) is lost. The "narrow core" approximation (3) is good provided $\Gamma \lesssim 1/2$, with the error at $\Gamma = 1/2$ being about 10 percent [12]. In principle, Γ could be pushed above 1/2, which would invalidate the solution above. An inspection of the exact form of Γ for the fundamental mode in a symmetric three-layer slab dielectric waveguide [12] shows, however, that Γ begins to saturate in this range, going over from the $\Gamma \propto h^2$ dependence at $\Gamma < 1/2$ to $\Gamma \propto h^p$ with gradually decreasing $p < 1$ for $\Gamma \gtrsim 1/2$. Therefore, α_{eff} has its optimum value for those r which correspond to $\Gamma \approx 1/2$. Physically, as the superlattice is made thicker to absorb the wings of the light intensity distribution, the SLS requirement of decreasing r leads to less efficient absorption at the peak intensity, thus more than offsetting the gain.

Setting $\Gamma = 1/2$ in (3) with $h \rightarrow h_{\text{SLS}}^{\max}$, taking $\lambda = 1.3\ \mu$m and $x = 0.6$, and using (5), we find

$$h_{\text{SLS}}^{\max} \approx 1300\ \text{Å}/\sqrt{r}\,. \qquad (7)$$

Substituting this into (1) and (2) yields a transcendental equation for r, viz., $36.3r^{3/2} = \ln(335/\sqrt{r})$ with the solution $r \approx 0.3$, corresponding to $h_{\text{SLS}}^{\max} \approx 2400$ Å. Thus we can expect an optimum value $\alpha_{\text{eff}} \lesssim 0.2\alpha \approx 20\ \text{cm}^{-1}$ in an SLS consisting of 12 periods of 60 Å $\text{Ge}_x\text{Si}_{1-x}$/140 Å Si.

This means that the waveguide length must be of order 0.5 mm for high detector efficiency. If a p-i-n detector represents a ridge waveguide of that length and the width $\lesssim 10\ \mu$m, then its capacitance is less than about 0.5 pF, assuming a typical depletion width of 1 μm. This value of the internal capacitance is acceptable and comparable to that of the conventional p-i-n IR detectors.

The detector sensitivity will be further improved by an avalanche gain in Si cladding layers. To reduce an excess noise, the APD design should be guided by the following principles: 1) since $k \equiv \alpha_p/\alpha_n \ll 1$ in Si, the multiplication should be initiated by electrons rather than holes; 2) since k^{-1} decreases sharply when the electric field much exceeds the ionization threshold E_i the field in the avalanche layer should be near the threshold $E \gtrsim E_i \approx 3 \times 10^5$ V/cm, and the thickness of that layer should be well above $\alpha_n^{-1}(E_i) \approx 0.5$ μm; and 3) the field in the SLS layers should not exceed $\sim 10^5$ V/cm, the ionization threshold in Ge.

A possible waveguide APD structure is illustrated in Fig. 3. In addition to an undoped $\text{Ge}_x\text{Si}_{1-x}$/Si SLS of $x \gtrsim 0.6$, $r \lesssim 0.3$, and thickness $h_{\text{SLS}} \gtrsim 2400$ Å, it 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 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 $\epsilon E_i \approx 2 \times 10^{12}\ e/\text{cm}^2$. This will achieve the desirable high-low field separation of the absorption and multiplication layers and result in a low-noise SAM APD structure.

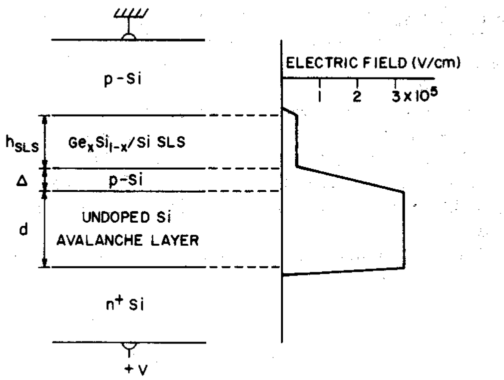

Fig. 3. A waveguide APD structure and the electric field profile.

To summarize, we have proposed and theoretically justified a novel IR photodetector structure for fiber-optics communications. Its principle is based on waveguiding and absorption of IR radiation in a strained-layer $\text{Ge}_x\text{Si}_{1-x}$/Si superlattice core and a subsequent injection of photogenerated carriers into Si cladding layers. We have predicted an optimum composition of the core, as determined by a trade-off between the confinement of radiation and the stability requirements for a $\text{Ge}_x\text{Si}_{1-x}$/Si SLS. We have also discussed the design of a SAM APD waveguide structure, in which low-noise avalanche multiplication occurs in one of the Si cladding layers. Experimentally, such structures have been recently manufactured by molecular beam epitaxy and tested [11], [13]. The first SLS waveguide p-i-n diodes [11] showed an internal quantum efficiency of 40 percent at $\lambda = 1.3\ \mu$m and a frequency bandwidth of close to 1 GHz. The first APD structure [13] showed an avalanche gain as high as $M = 50$ and a quantum efficiency of 100 percent at $M = 10$. Our approach is entirely compatible with the Si integrated circuit technology and offers the possibility of fabricating a complete receiver system for long wavelength fiber-optics communications on a silicon chip.

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