Avalanche Gain in Ge_xSi_{1-x}/Si Infrared Waveguide Detectors

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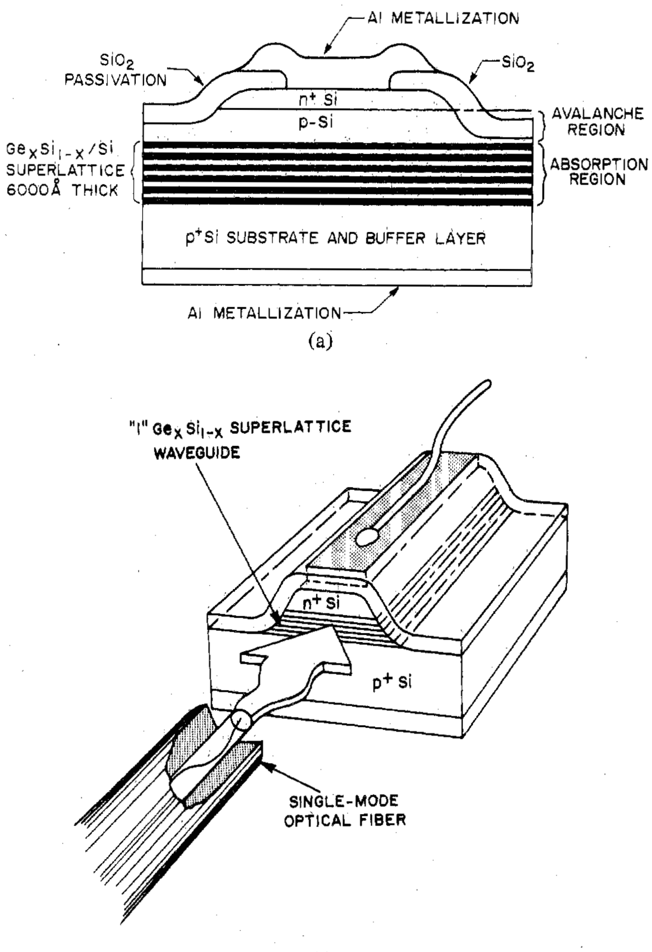
Abstract—**Avalanche gain in Ge_xSi_{1-x}/Si heterostructures photodiodes has been measured for the first time. Absorption of infrared radiation occurs in a Ge_xSi_{1-x}/Si strained-layer superlattice (SLS) which serves as a waveguide core, and the avalanche multiplication takes place in one of the Si-cladding layers. Multiplication factors as high as 50 have been obtained for a 1.1-μm wavelength response ($x = 0.2$). The external absolute sensitivity operating at a multiplication of 10 is 1.1 A/W at 1.3 μm for an uncoated device.**

ALTHOUGH Si photodiodes [1] are well-known for their excellent performance and high reliability, their use in optical fiber communication links at 1.3 or 1.5 μm has not been possible because the optical absorption of Si cuts off at 1.1 μm—far short of the optimum window for optical fiber communications. Other semiconductor materials, notably Ge [2] and GaInAs [3] are under development to overcome this gap. However, avalanche photodiodes made from these materials suffer from a very large excess noise factor, near the theoretical maximum, resulting from nearly equal ionization rates for electrons and holes [4], [5]. One single feature which distinguishes avalanche gain in Si from other photodiode materials is that the excess noise factor in Si avalanche photodiodes is near the *minimum* theoretical value [6].

The ideal solution to this problem would be an avalanche photodiode with optical properties similar to those of Ge but with the noise properties of Si. In this paper we report substantial progress along these lines with the successful fabrication and testing of an avalanche photodiode which shows promise in meeting these two goals.

Our devices were produced on 3-in Si wafers by molecular-beam epitaxy (MBE) [7]. The schematic cross section of a typical wafer is shown in Fig. 1(a). The basic features of this structure are: a) a silicon buffer layer, and b) a strained-layer superlattice (SLS) consisting of alternate layers of Si and Ge_xSi_{1-x} and a top layer of Si. The p-n junction is formed either during growth, or subsequent to growth using ion implantation. All steps used during fabrication—plasma etching oxidation, oxide deposition, ion implantation, and metallization—are standard VLSI processing techniques. The strained layer epitaxy allows us to extend the thickness of the absorption region well beyond the 100 Å critical thickness without introducing additional lattice-mismatch defects in the grown material. For example, the maximum single layer thickness for an alloy of 60-percent Ge and 40-percent Si on Si would be about 50 Å before the onset of misfit dislocations [8]. When 30-Å layers of this material sandwiched between 290-Å-thick layers of Si are incorporated in a strained-layer superlattice, we can increase the total thickness to 6000 Å. It has been shown by Hull *et al.* [9] and by People [10] that the maximum thickness of the superlattice region before the onset of strain-induced dislocations corresponds to the maximum thickness of the homogeneous alloy layer whose composition is the same as the *averaged* composition of the superlattice region. It has been shown by us [11] that the optimum total thickness for the superlattice waveguide region is determined



(a)

(b)

Fig. 1. (a) Schematic diagram of epitaxial structure showing layer doping and compositions. Typical superlattice thicknesses used range from 0.5 to 2.0 μm. (b) Light-coupling geometry for waveguide coupling. Fiber lensing, not used in our measurements, could be employed to enhance the coupling efficiency.

Manuscript received January 20, 1986; revised February 28, 1986.
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IEEE Log Number 8608818.

0741-3106/86/0500-0330$01.00

by constraints related to the lattice mismatch strain on the one hand and maximization of absorption of the optical field in the waveguide on the other. These considerations indicate that a total thickness of ~2500 Å, with appropriate adjustments to the superlattice composition and geometry, may be preferable.

Light is coupled into the photodiodes, as shown in Fig. 1(b), in the plane of the SLS which also acts as a waveguide. In bulk unstrained material the indirect bandgap of the $Ge_{0.6}Si_{0.4}$ alloy composition occurs at 0.89 eV corresponding to a wavelength of 1.4 μm. However, it has recently been proposed on the basis of theoretical work by People [12] that the lattice mismatch strain (nearly 3 percent in our samples!) extends the absorption edge to 1.6 μm for this alloy composition. This has been recently verified by experiments of Lang *et al.* [13]. We have exploited this effect in the design of the absorption region. The device geometry is rectangular, 50 μm wide, and of various lengths from 50 to 500 μm. Devices were separated from the wafer by cleaving. Devices were illuminated using a single-mode optical fiber butt-coupled to the device. Coupling light from the fiber is facilitated by the large numerical aperture (na ≅0.5) of the SLS absorption waveguide. Unity-gain external quantum efficiency at 1.3 μm is about 10 percent for the $Ge_{0.6}Si_{0.4}$ alloy. The superlattice structure was a sandwich of 33 Å of $Ge_{0.6}Si_{0.4}$ between 290 Å of Si. The characteristic spectral response for this and other alloy compositions has been published previously [14].

The log-current voltage characteristic in reverse bias for the $n^+ - p - p^+$ structure in Fig. 1(a) is shown in Fig. 2. Breakdown is indicated by the sharp knee near 30 V. A standard Si diode with this breakdown voltage has a carrier concentration of $\sim 3 \times 10^{16}$ cm^{-3}. The carrier concentration of our structure was determined from *CV* profiling to be 4×10^{16} cm^{-3}. This correspondence suggests that reverse breakdown occurs as desired from avalanche in Si and not in the lower bandgap regions. The temperature dependence of the breakdown voltage was taken between 20°C and 150°C, and the results confirm that reverse breakdown occurs from the avalanche effect. The breakdown voltage increases with temperature as shown in Fig. 3. The measured coefficient is +0.03 V/°C, which is similar to that in Si as determined by Goetzberger [15].

Avalanche multiplication of the optical signal from a 1.3-μm laser was measured as a function of frequency for these devices which were not anti-reflection coated. No rolloff of multiplication was measured as a function of frequency from dc to 1 GHz. At 1.3 μm a maximum gain of 10 was obtained before the onset of microplasmas, for a structure in which the avalanche region was not optimally separated from the absorption region because of the doping-thickness product of the avalanche region was too large. The maximum absolute external sensitivity obtained was 1.1 A/W. This figure can easily be improved with lensing of the fiber and adjustments to the geometry of the SLS waveguide. These measurements were made on detectors 250 μm in length. The low value of external quantum efficiency is a result of nonoptimized coupling, waveguide scattering, and low absorption coefficient. Higher multiplications have been obtained in wafers with a lower Ge content. These wafers, containing 2000 Å of $Ge_{0.2}Si_{0.8}$ sandwiched between 2000 Å of Si, have a shorter wavelength absorption near 1.2 μm. For a series of diodes with maximum response at 1.1 μm, gains of more than 50 are routinely measured near breakdown. These photodiodes were made using separate absorption and multiplication regions, carefully designed so that the electric field in the absorption region remained below threshold for impact ionization, but high enough to ensure a rapid sweepout of photocarriers. The higher gain obtained in these devices may reflect the difference in structure employed or reduced strain because of the lower alloy content ($x = 0.2$). For these diodes, the multiplication as a function of bias voltage is shown in Fig. 4.

In conclusion, we have demonstrated avalanche gain in Ge_xSi_{1-x}/Si photodiodes at 1.1 and 1.3 μm. Our results indicate considerable promise for this MBE-grown structure in optical communications and other detector applications. We are currently packaging these diodes for excess noise testing. The excess noise factor cannot be determined from ionization

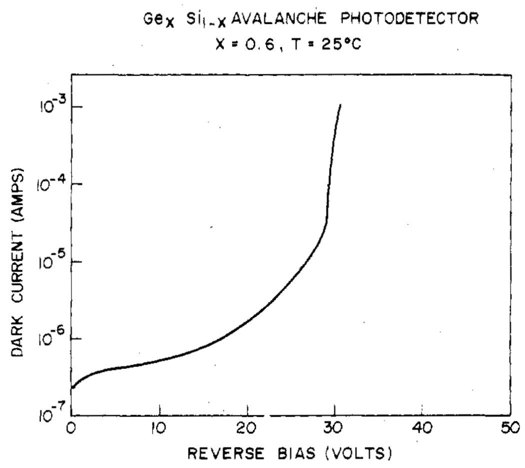

Fig. 2. Reverse log *I-V* characteristic for an n$^+$-p diode. Diode area is 5×10^{-5} cm^2. Sharp breakdown is seen near 30 V. The breakdown voltage is in good agreement with the carrier concentration determined from *CV* profiling.

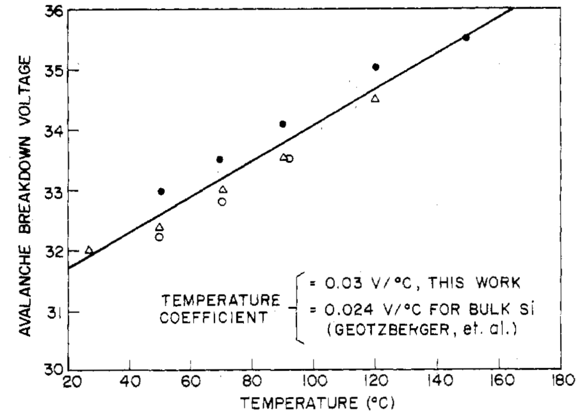

Fig. 3. The temperature dependence of the breakdown voltage is positive, as expected for avalanche breakdown. Tunneling breakdown has a negative temperature coefficient. Results are shown for three different samples, with compositions in the absorption region ranging between $x = 0.2$ and $x = 0.6$.

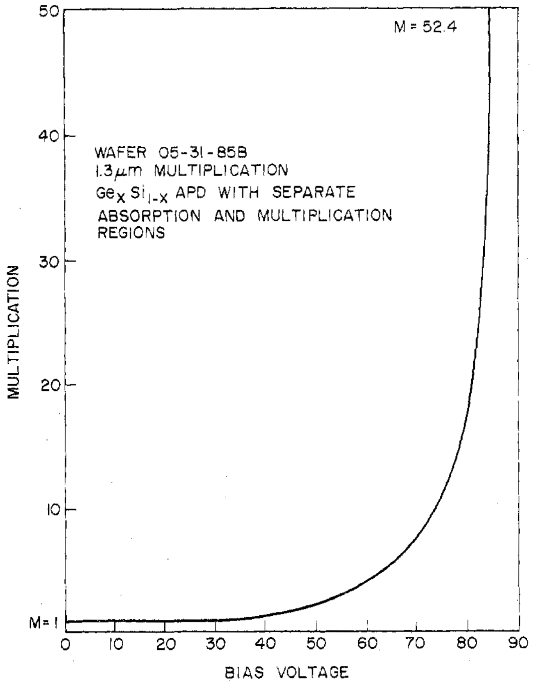

Fig. 4. Carrier multiplication versus voltage for a avalanche photodiode with maximum response near 1.1 μm. The maximum gain at breakdown is over 50. Previous measurements on Si photodiodes indicate an excess noise factor [1] close to 5 at this gain. By comparison, the same excess noise factor of 5 is measured in InP-based avalanche diodes [4] at a gain of only 10.

rate measurements because the SLS structure does not permit separate injection of electrons and holes.

ACKNOWLEDGMENT

The authors acknowledge helpful discussions with D. V. Lang, K. Cunniff, R. People, and T. Seidel, and the expert assistance of J. Blakeslee, R. T. Lynch, E. A. Sadowski, and R. D. Yadvish. We wish to thank M. B. Panish and V. Narayanamurti for their continuing support of this work.

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