1.3 μm photoresponsivity in Si-based $Ge_{1-x}C_x$ photodiodes

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(Received 2 December 1997; accepted for publication 12 February 1998)

$Ge_{1-x}C_x$/Si heterostructure photodiodes with nominal carbon percentages $(0 \leq x \leq 0.02)$, which exceed the solubility limit, were grown by solid source molecular beam epitaxy on *n*-type (100) Si substrates. The p-$Ge_{1-x}C_x$/n-Si photodiodes were fabricated and tested. The p-$Ge_{1-x}C_x$/n-Si junction exhibits diode rectification with a reverse saturation current of about 10 pA/μm^2 at -1 V and high reverse breakdown voltage, up to -80 V. A significant reduction in diode reverse leakage current was observed by adding C to Ge, but these effects saturated with more C. Photoresponsivity was observed from these Si-based p-$Ge_{1-x}C_x$/n-Si photodiodes at a wavelength of ≥ 1.3 μm, compatible with fiber optic wavelengths. External quantum efficiency of these thin surface-normal photodetectors was measured up to 2.2%, which decreased as the carbon percentage was increased.
 [S0003-6951(98)00915-2]

Integration of cost effective photonic devices with mature Si-based microelectronic technology remains an area of intense research.[1–3] Current optoelectronic communication systems are based upon expensive but high performance III-V compound optoelectronic components and often cumbersome hybrid integration schemes. One such effort to realize affordable and easily mass-produced optoelectronic integrated circuits (OEICs) which could potentially impact the consumer market involves Si-based optoelectronic devices. These devices need to be monolithically integrated with Si-based microelectronics and operate in the infrared wavelength region, suitable for fiber-optic communications.

One such candidate is Group IV semiconductor alloys and heterostructures.[1–3] In the past decade, most work on Group IV semiconductors has focused on strained Si-rich SiGe alloys on Si substrates. To achieve an efficient photoresponse at the 1.3 μm wavelength region with SiGe/Si photodetectors, the Ge concentration should be in excess of 35%. However, the 4% lattice mismatch between Si and Ge constrains the design of SiGe heterojunction devices because of the limited critical thickness for pseudomorphic SiGe epilayers on a Si platform.[2]

Incorporation of C into Si and Ge to form $Ge_{1-x}C_x$ and the ternary alloy $Si_{1-x-y}Ge_xC_y$ makes it possible to reduce the compressive strain between the SiGe epilayer and the Si substrate, and therefore to control the strain about the lattice matching condition for Si substrates while allowing adjustable band gaps.[4–6] However, due to the low solubility of C in Ge (10^8 atoms/cm^3 at the melting point of Ge),[7] it is considerably difficult to obtain large fractions of C in Ge. $Ge_{1-x}C_x$ is predicted to be thermodynamically unstable in solid state form,[8] decomposing into its segregated components under zero pressure. But, nonequilibrium growth techniques, such as molecular beam epitaxy (MBE) or rapid thermal chemical vapor deposition (RTCVD), can synthesize $Ge_{1-x}C_x$ alloys with small percentages of carbon (under 3% by MBE[9] and 5% by RTCVD).[10]

This work has concentrated on the binary $Ge_{1-x}C_x$ alloy. Previous research on the $Ge_{1-x}C_x$ system has centered mostly upon its material properties. Our own investigations explored processing issues[11] and now device performance, using these new Group IV alloys. In this letter, we report on the fabrication and characterization of p-$Ge_{1-x}C_x$/n-Si heterojunction photodiodes grown by MBE with $(0 \leq x \leq 0.02)$, nominally. Our diodes demonstrate that rectification and diode leakage significantly improves by adding C to Ge. Photoresponsivity to 1.3 μm light, suitable for fiber optic systems, was observed for the p-$Ge_{1-x}C_x$/n-Si photodiodes which were based upon a Si platform.

The normal-incidence heterojunction *p*-*n* photodiodes were fabricated from p-$Ge_{1-x}C_x$ epilayers grown on (100) *n*-Si substrates by MBE in an EPI 620 system. Details of the $Ge_{1-x}C_x$ growth are described elsewhere.[9] The carrier concentration of the *n*-Si substrates was 10^{14}–10^{15} cm^{-3}. The $Ge_{1-x}C_x$ bulk epilayers were *in situ* doped *p* type by a concurrent B flux, using an effusion cell loaded with pure B in a pyrolytic graphite crucible and all epilayers were about 0.6 μm thick. Information on the composition, doping and thickness of the p-$Ge_{1-x}C_x$ epilayers used in this study is listed in Table I. The nominal C compositions were determined from the growth conditions, which were calibrated from other samples.

The substrate temperature during MBE growth was kept constant at 400 °C. This temperature produces layer-by-layer growth of $Ge_{1-x}C_x$ to avoid growth front roughness, which occurs at elevated temperatures.[12] Also, this growth temperature minimizes outdiffusion of the B dopant into the Si substrate, and junction displacement. These Ge-rich layers were confirmed to be single crystal with good crystallinity away from the interface by channeling Rutherford backscattering (RBS). For epilayers greatly exceeding the critical thickness, it is expected that the epilayers should be relaxed with a high

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TABLE I. Selected information on the material properties, including composition, doping level, and epilayer thickness of the samples used in this study along with representative diode characteristics of the p-$Ge_{1-x}C_x/n$-Si heterojunction photodiodes, including dark current at selected bias points, ideality factor and external quantum efficiency (EQE) at 1.3 μm.

Sample Number	SGC174	SGC173	SGC175	SGC236
Nominal composition	$Ge_{0.992}C_{0.008}$	$Ge_{0.986}C_{0.014}$	$Ge_{0.98}C_{0.02}$	Ge
P-type doping level (cm^{-3})	2.7×10^{18}	2.1×10^{18}	1.5×10^{18}	2.0×10^{18}
Thickness (nm)	590 (RBS)[a]	610 (RBS)[a]	645 (RBS)[a]	600 (GC)[b]
Dark current (pA/μm^2)				
@−1 V	14	12	10	414
@−20 V	73	34	46	1800
Ideality factor	1.08	1.07	1.05	1.19
External quantum efficiency (%)				
@1.3 μm	2.2	2.0	1.3	2.2
corrected	2.8	2.5	1.6	2.8

[a]RBS: determined by RBS measurements.
[b]GC: estimated from growth condition.

density of defects, including misfit and threading dislocations. This was confirmed by transmission electron microscopy (TEM) in cross-sectional views on similar layers, which showed dislocation densities about 10^{10} cm^{-2}.

$Ge_{1-x}C_x$ mesas, which were 97 μm in diameter, were formed by photolithography and wet etching into the Si substrate, using a $H_3PO_4:H_2O_2:H_2O$ etchant.[13] A second photolithography defined the annular ohmic contact (94 μm outer diameter and 54 μm inner diameter), using standard liftoff technology. A Ti/Au bilayer was deposited by electron beam evaporation atop the mesa. The backside ohmic contact on the Si substrate was formed by e-beam evaporation of Ti/Au on the entire backside of the substrate. The samples then underwent heat treatments in a forming gas (15% H_2-N_2) ambient at 300 °C for 30 s in a Heatpulse 610 rapid thermal annealing (RTA) furnace. Adjacent to the diodes were transmission line method (TLM) test structures for measuring the ohmic contact resistance of the $Ge_{1-x}C_x$ contacts. The metal contacts were determined to be ohmic, with a specific contact resistance of under 2×10^{-6} Ω cm^2.

The current–voltage ($I-V$) characteristics of the p-$Ge_{1-x}C_x/n$-Si diodes were measured and are shown in Fig. 1. The $Ge_{1-x}C_x$/Si structures exhibit diode rectification. All the diodes exhibited reverse breakdown voltage of −60 to −80 V, irrespective of the C concentration varying from 0% to 2%. The measured reverse saturation currents of the three p-$Ge_{1-x}C_x/n$-Si diodes at −20 V and −1 V are in the range of 34–74 pA/μm^2 and 10–14 pA/μm^2, respectively (Table I). No clear dependence of leakage current on the C concentration was observed for any of the p-$Ge_{1-x}C_x/n$-Si diodes. This measured leakage current is comparable to a reported leakage current density of 70 pA/μm^2 for a $Si_{0.385}Ge_{0.600}C_{0.015}$ p-i-n photodetector.[14] The p-Ge/n-Si diode (SGC236) control diode with 0% C exhibits a much larger reverse saturation current, as shown in Fig. 1, than diodes which include C in the active region. This large change of reverse saturation currents between $Ge_{1-x}C_x$ diodes with C and without C agrees with earlier results.[15] The C may improve the Ge/Si interface quality and consequently the diode properties, but the small differences observed among the three p-$Ge_{1-x}C_x/n$-Si diodes could be due to the small variation in C composition. Therefore, a small amount of C can have a profound impact on leakage, but adding more C leads to diminishing returns.

The I-V curves of the p-$Ge_{1-x}C_x/n$-Si diodes (Fig. 1) all show a low turn on voltage of only 0.15–0.2 V for the p-n $Ge_{1-x}C_x$/Si heterojunctions regardless of C composition. A large series resistance in the low-doped Si substrate made extrapolation of the ideality factor, but an improvement of diode properties by adding C to Ge was observed. A summary of the diode I-V characteristics is listed in Table I.

Photoresponsivity was observed for all the $Ge_{1-x}C_x$/Si heterojunction diodes using laser excitation at a wavelength of 1.3 μm, which is below the Si band gap ($\lambda_g=1.1$ μm). The laser beam was focused within the inner circle of the annular contact onto the bare $Ge_{1-x}C_x$ surface. Photocurrents were measured in these diodes which lack any antireflection coatings and are shown in Fig. 2. The external quantum efficiencies (EQE) were calculated (see Table I). To account for the fraction of the incident laser spot falling outside the central window area and is reflected off the annular metal contact, a correction factor of about 0.8 was multiplied by the total incident light power, assuming a two-

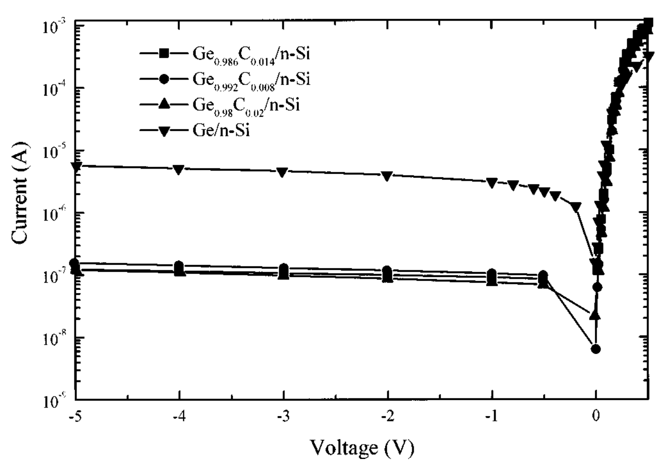

FIG. 1. The measured I-V characteristics (semi-log form) of the p-$Ge_{1-x}C_x/n$-Si diodes with 0%, 0.8%, 1.4%, and 2.0% carbon.

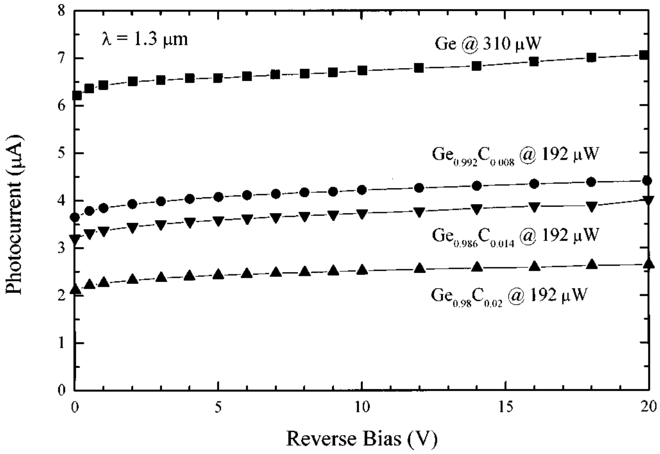

FIG. 2. The measured photocurrent for the p-$Ge_{1-x}C_x/n$-Si photodiodes with 0%, 0.8%, 1.4%, and 2% carbon and incident 1.3 μm illumination.

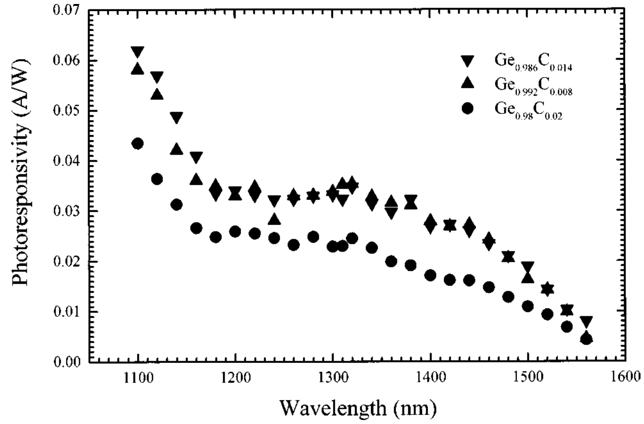

FIG. 3. The spectral photoresponsivity of the p-$Ge_{0.992}C_{0.008}/n$-Si, p-$Ge_{0.986}C_{0.014}/n$-Si, and p-$Ge_{0.98}C_{0.02}/n$-Si photodiodes. Note the elevated response at 1.1 μm due to the Si substrate.

dimensional (2D) Gaussian distribution for the incident light. The corrected EQEs are given in Table I.

Spectral dependence of the photoresponsivity was measured, as shown in Fig. 3. Note the elevated response for wavelengths below 1.1 μm where the absorption edge of the Si substrate becomes prominent. It is expected that there is a dependence of 1.3 μm photoresponsivity on C concentration, because substitutional C will increase the band gap of the $Ge_{1-x}C_x$ alloys and cause a blueshift of the absorption edge. This was shown with absorption studies for $Ge_{1-x}C_x$ (Ref. 16) and Ge-rich $Si_{1-x-y}Ge_xC_y$ alloys.[17] From these studies the $Ge_{1-x}C_x$ band gap is expected to have a +63 meV/%C dependence. A significant drop in photoresponsivity for the p-$Ge_{0.98}C_{0.02}/n$-Si photodiodes compared to other p-$Ge_{1-x}C_x/n$-Si photodiodes was observed over the infrared region. Therefore, there may be a nonlinear dependence on EQE with increasing C. Also, a flat response is indicated between 1.2 and 1.3 μm which could be attributed to a defect level at 0.767 eV, a possible Si P-line, previously discovered in photoluminescence measurements of similar $Ge_{1-x}C_x$/Si layers.[13] However, it is clear that a small amount of C acts to significantly improve leakage currents without significantly affecting the 1.3 μm photoresponsivity.

The results of 1.3%–2.2 % quantum efficiency are significant not only because they are greater than the best result reported in normal incidence SiGeC p-i-n photodetectors, but also because the diodes did not have an anti-reflection (AR) coating and the light collection region is confined to a narrow region at the p^+-$Ge_{1-x}C_x/n^-$-Si one-sided junction. This leads to a much shorter collection length within the p^+-$Ge_{1-x}C_x$ depletion region and within a diffusion length than previous SiGeC p-i-n photodetectors which reported an EQE of ~1% at 1.3 μm, using an 800 Å thick active region.[14]

In conclusion, p-n photodiodes made from a heterojunction of epitaxial p-type $Ge_{1-x}C_x$ with nominal carbon percentages ($0 \leqslant x \leqslant 0.02$) on an n-type Si substrate were demonstrated. The I-V curves indicate that the p-Ge/n-Si diode exhibits a much larger reverse saturation current (~400 pA/μm^2 at −1 V) than that of a comparable p-$Ge_{1-x}C_x/n$-Si diode (10 pA/μm^2 at −1 V), suggesting that C could improve the $Ge_{1-x}C_x$ epilayer quality and suppress photodiode dark currents. High reverse breakdown voltages in excess of −60 and some up to −80 V are observed in all of the p-$Ge_{1-x}C_x/n$-Si diodes, including the p-Ge/n-Si diode. Despite the large number of dislocations and defects at the heterojunction, photoresponses with a measured EQE of 1.3%–2.2% from the $Ge_{1-x}C_x$ epilayers were observed by 1.3 μm laser excitation, and allow fiber-optic compatible photonics on a Si platform. There may be some nonlinear dependence of EQE on carbon concentration.

The authors wish to thank J. O. Olowolafe for useful discussions. This work was supported by the National Science Foundation (Grant No. ECS-9624160) and by DARPA (sponsored Research Agreement with Texas Instruments, Inc. under Grant No. SRA-3312665).

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