Current Transport Characteristics of SiGeC/Si Heterojunction Diode

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***Abstract*— The characteristics of heterojunction diodes fabricated from p-type epitaxial $Si_{0.07}Ge_{0.91}C_{0.02}$ alloy grown by molecular beam epitaxy on n-type Si (100) have been examined by using current–voltage, capacitance–voltage, and Hall effect measurements. The SiGeC/Si heterojunction diode shows good rectification with nearly ideal forward bias behavior and low reverse leakage currents compared to Ge/Si heterojunction diodes. The temperature dependence of the current-voltage behavior indicates that the principle conduction mechanism is by electron injection over a barrier. Reverse breakdown occurs by the avalanche mechanism.**

I. Introduction

RECENTLY there has been a growing interest in heterojunction (HJ) devices compatible with silicon. Doped layers of $Si_{1-x}Ge_x$ alloys have improved the performance of bipolar transistors [1] and have produced light emitting diodes [2]. SiGe alloys, however, are lattice-mismatched to Si substrates. The addition of C to SiGe helps with strain compensation, and affects the interface, bandgap energy and the energy band offsets [3]. Although the structural and optical properties of $Si_{1-x-y}Ge_xC_y$ alloys have been reported [4], [5], the electrical properties are not yet well understood.

This paper examines the electrical properties versus temperature of $Si_{1-x-y}Ge_xC_y$/Si p^+-n heterojunction diodes fabricated from mesa-etched epitaxial layers grown on n-type Si-substrates by molecular beam epitaxy (MBE). We focus on the behavior of Ge-rich layers of composition $Si_{0.07}Ge_{0.91}C_{0.02}$ heavily doped with boron to produce p-type conductivity. We have shown that the valence band offset (ΔE_v) between bulk $Si_{0.07}Ge_{0.91}C_{0.02}$ and Si is about 0.60 eV [6], and this is large enough to impede the injection of holes from SiGeC into Si.

II. Experimental Detail

The SiGeC layers were grown in an EPI 620 MBE system on 75-mm diameter (100) oriented Si substrates at a temperature of 550 °C as previously described [4]. Solid elemental sources were used, and the boron cell temperature was 1550 °C for the doping concentration used here. The relatively low substrate growth temperature minimizes the interdiffusion between the layer and substrate. The heterojunction, therefore, is expected to be abrupt. The doped SiGeC layer reported here was 0.18-μm thick and the doped Ge layer was 0.5 μm. Electron diffraction showed the SiGeC layer to be single crystal. From Hall effect measurements, the hole concentrations were 1×10^{19} cm^{-3} in the SiGeC and 5×10^{18} cm^{-3} in the Ge. The hole mobility of $Si_{0.07}Ge_{0.91}C_{0.02}$ at room temperature (90 cm^2/V·s) was somewhat lower than in pure Ge perhaps due to additional alloy scattering, but it was 1.5 times higher than the mobility in pure Si. From conductivity measurements, the n-type Si substrate doping was about 2.5×10^{15} cm^{-3}. Optical absorption measurements of the doped $Si_{0.07}Ge_{0.91}C_{0.02}$ indicated a bandgap of 0.80 eV, but this value may be larger than the effective bandgap because of impurity band absorption. Standard optical lithography and wet chemical etching were used to form the diodes shown schematically in Fig. 1. The SiGeC layers were mesa etched in a $H_3PO_4 : H_2O_2 : H_2O$ (1 : 6 : 3) solution for 1.5 min to a depth of 0.18 μm. Electron beam evaporated Ti/Au metal layers of thickness 300 Å/1500 Å were used for both the p- and n-contacts without annealing. The contacts were patterned by the lift-off method. The mesa area was 2.2×10^{-3} cm^{-2}. The Ti/Au were measured to have ohmic, linear current voltage characteristics over the full measurement range.

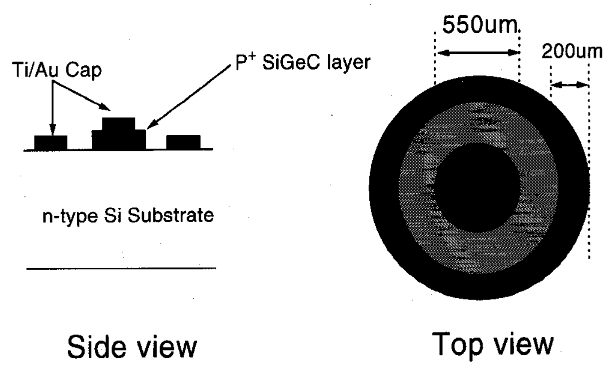

Fig. 1. Schematic cross section and top view of the mesa etched diodes fabricated in 0.18-μm thick p-SiGeC layer on n-Si (100) substrate.

III. Results and Discussions

To provide information on the transport mechanisms, the current-voltage (*I–V*) characteristics were measured versus temperature. Fig. 2 shows the *I–V* characteristics for three

Manuscript received June 19, 1996; revised August 6, 1996. This work was supported by the AFOSR under Grant F49620-95-1-0135, the ARO under Grant DAAH04-95-1-0625, the ONR under Grant N00014-93-1-0393, the DARPA contract F49620-96-C-006, and by W. L. Gore & Associates.

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Publisher Item Identifier S 0741-3106(96)08869-6.

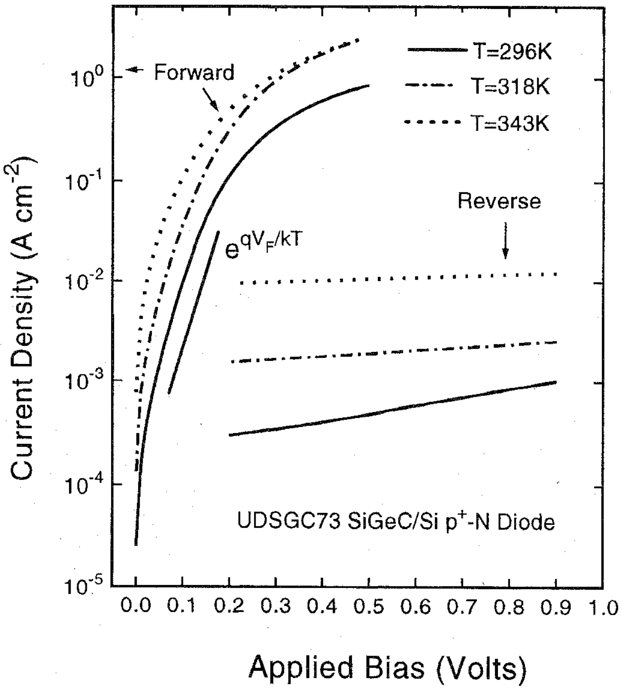

Fig. 2. I–V characteristics of SiGeC/Si p$^+$-n heterojunction diode. Diodes are strongly rectifying with nearly ideal behavior at room temperature. In forward bias, ideality factor near unity implies injection over a barrier.

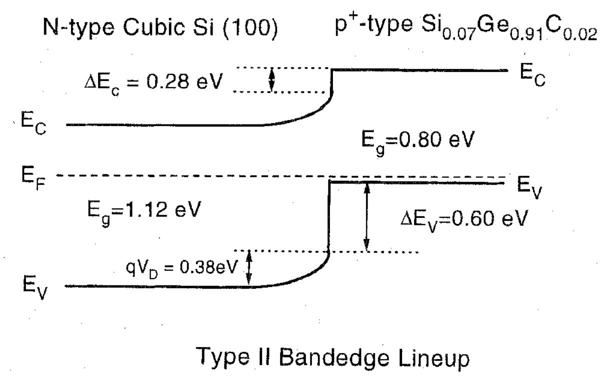

Fig. 3. Energy-band diagram of $Si_{0.07}Ge_{0.91}C_{0.02}$/Si heterojunction. Most of band bending occurs in Si substrate since the SiGeC is more heavily doped. The diagram is calculated using $\Delta E_V = 0.60$ eV and $E_g = 0.80$ eV. Energy band alignment is staggered, type II.

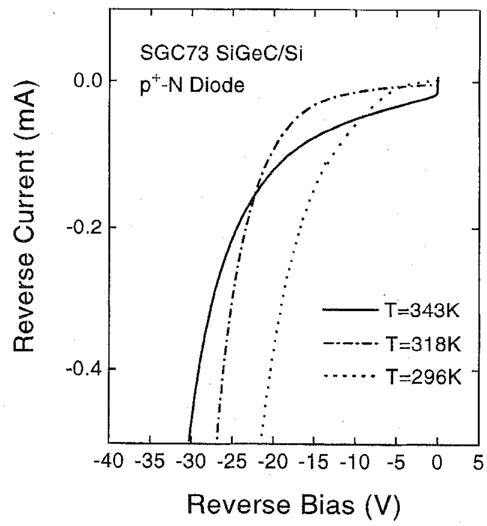

Fig. 4. Temperature dependence of SiGeC/Si heterojunction breakdown voltage, implying an avalanche mechanism.

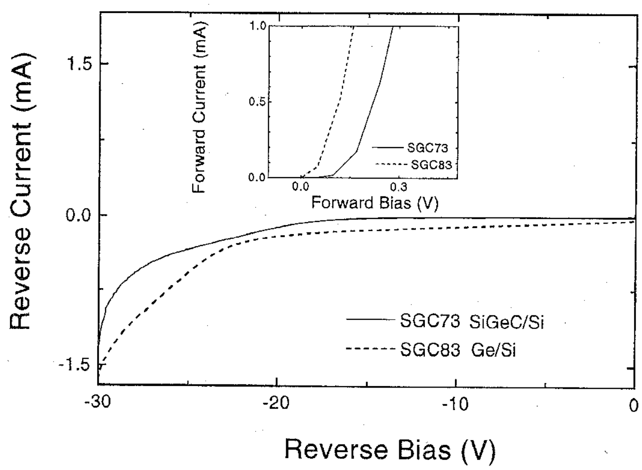

Fig. 5. I–V characteristics for SiGeC/Si and Ge/Si diodes. The SiGeC/Si diode has I–V characteristics with smaller leakage current, higher breakdown voltage, and higher turn-on voltage.

temperatures from 296 K to 343 K. At low bias at room temperature, the characteristics were nearly ideal with $\eta = 1.1$, where $I = I_0 \exp(qV/\eta kT)$. The deviation from linearity at high forward current may be due to series resistance and high level injection. The forward turn-on voltage is relatively low compared to a pure Si homojunction. Low forward turn-on voltages in heterojunctions are associated with low bandgaps and low values for one of the band offset energies [7], [8]. The forward current increases exponentially with temperature implying thermally activated behavior. The SiGeC/Si diodes exhibit strong rectifying behavior. At biases more positive than -3 V, the reverse current magnitude increases with temperature. At biases more negative than -3 V, the effect of the breakdown voltage, which increases in magnitude with temperature, causes the temperature curves to cross. A plot of $I(dV/dI)$ versus I at $T = 296$ K gives the ideality factor $\eta = 1.1$ from the intercept, and the series resistance $r_s = 138\ \Omega$ from the slope. From the value of η, we infer that the principal forward current mechanism is due to carrier injection over a barrier. Assuming an exponential dependence of saturation current of I_o on temperature, where $I_o \sim \exp(-\Delta E_{AF}/kT)$, the activation energy ΔE_{AF} for the current was obtained from an Arrhenius plot of current versus temperature from 296 K to 343 K at different forward biases. Extrapolation to zero bias yields an activation energy of 0.38 eV. We note that this value is approximately $E_g/2$ using the value $E_g = 0.8$ eV measured from optical absorption, and may indicate the activation energy for electron generation/recombination current in the diode.

This value is also consistent with capacitance–voltage (*CV*) measurements of $1/C^2$ versus V which extrapolate to yield the built-in voltage V_{bi} of 0.38 V. The linearity of the $1/C^2$-V characteristics implied a uniformly-doped abrupt junction. An energy-band diagram of a $Si_{0.07}Ge_{0.91}C_{0.02}$/Si heterojunction, based on the experimental valence-band offset and bandgap data, is shown in Fig. 3. The conduction-band discontinuity $\Delta E_C = 0.28$ eV and the valence-band discontinuity $\Delta E_V =$ 0.60 eV. Since ΔE_V is large enough to impede the injection of holes from SiGeC to Si, and is larger than ΔE_C, therefore, we expect that the transport current is mostly due to the injection of electrons from the n-Si into the p-SiGeC.

The reverse current characteristics versus temperature near breakdown are shown in Fig. 4. The breakdown voltage near -20 V corresponds to a critical field $\epsilon_{\rm cri} = 2.2 \times 10^5$ V/cm which is between the values for Si (3×10^5 V/cm) and Ge (10^5 V/cm). At $T = 296$ K, the prebreakdown current obeys the $I_R \sim (V)^m$ where $m \approx 2.5$ which we attribute to tunneling and surface leakage. At higher temperature, however, the thermal current with $m \approx 1$ dominates. The voltage at which reverse breakdown occurred increased with temperature suggesting an avalanche mechanism.

We compared our SiGeC/Si HJ diode to Ge/Si and SiGe/Si HJ diodes. Fig. 5 shows the *I–V* characteristics for both SiGeC/Si and Ge/Si HJ diodes with the same device area and similar doping level. The SiGeC/Si diode yielded *I–V* characteristics with smaller leakage current, higher breakdown voltage and higher turn-on voltage. For comparison, Kamins [8] *et al.* reported SiGe/Si diodes with reverse leakage current density $J_R = 1 \times 10^{-7}$ Acm^{-2} at bias = -5 V compared to 10^{-3} Acm^{-2} for our diodes. The SiGe diodes have the forward current density $J_F = 5 \times 10^{-6}$ Acm^{-2} at bias = 0.2 V compared to 10^{-1} Acm^{-2} for our SiGeC diodes. The Kamins diodes, however, were Si-rich (22% Ge) and our diodes are Ge-rich (91% Ge).

IV. Conclusions

The characteristics of $Si_{1-x-y}Ge_xCy$/Si diodes and their temperature dependence were investigated. Current–voltage characteristics were nearly ideal at low forward bias at room temperature. The temperature behavior indicated a barrier height for carrier injection of 0.38 V. Due to expected large valence band offsets, we conclude that the conduction mechanism is the injection of electrons from the wider gap n-Si to the p^+-SiGeC layer. These results indicate that the SiGeC/Si heterostructure has good electrical properties and is promising for Si-based device applications.

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