Impact ionization coefficients in $Si_{1-x}Ge_x$

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We have measured the electron and hole impact ionization coefficients in $Si_{1-x}Ge_x$ alloys. Carrier multiplication measurements were made on relaxed $Si_{1-x}Ge_x$/Si diodes grown by gas source molecular beam epitaxy. The hole to electron impact ionization coefficient ratio, β/α, varies from 0.3 to 4 in the composition range of $x=0.08-1.0$. *© 1995 American Institute of Physics.*

In Si, α is known to be greater than β with a β/α ratio of 0.1–0.4 at 330 kV/cm.[1–4] On the other hand, in Ge, β/α equals 1.5–4[5–7] at the same electric field due to the low hole effective mass which allows the holes to gain energy more easily than in Si. With the exception of a recent theoretical study,[8] there is no report on the experimental determination of α and β in pseudomorphic or relaxed $Si_{1-x}Ge_x$ alloys. It is evident that the large changes in band gap and band structure between Si and Ge will have a profound influence on the values of α and β and the ratio β/α. In this letter, we report the experimental determination of these coefficients in relaxed $Si_{1-x}Ge_x$ alloys.

In this work the coefficients were determined from photocurrent data of p^+-$i(Si_{1-x}Ge_x)$-n^+ diodes ($0\leq x\leq 1$) grown by molecular beam epitaxy using Si_2H_6 (disilane) and solid Ge as sources.[9] The heterostructures were grown at temperatures ranging from 500 to 600 °C. The SiGe i-region is undoped and the n- and p-type regions are doped with PH_3 and B, respectively. Figure 1(a) shows the schematic of a typical diode designed and fabricated for pure electron injection. The carrier concentration profile of a typical diode, determined by spreading resistance analysis, is shown in Fig. 1(b). Mesa-shaped diodes, 150 μm in diameter, were made by standard photolithography and reactive ion etching with a SF_6/O_2 mixture. Evaporated Al was annealed at 450 °C to form ohmic contacts to both n- and p-regions.

We have deduced the coefficients $\alpha(E)$ and $\beta(E)$ from the measured current multiplication factors in $Si_{1-x}Ge_x$/Si diodes with different x. To inject pure electrons into the $Si_{1-x}Ge_x$ i-region of a p^+-i-n^+ diode, electron-hole pairs were generated by focusing a 488 nm Ar laser on the p^+ substrate of the mesa diodes. A lensed fiber was used to couple light into the devices. Pure hole injection in the same device was not possible because the top n^+ layer was not thick enough to absorb all the light at $\lambda=488$ nm. Similarly, it was not possible to inject pure electrons in a n^+-i-p^+ diode. We have, therefore, determined both α and β from a single measurement of the multiplication factor M_n (or M_p) by using the equations outlined below.

Experimental results of impact ionization coefficients in Si and Ge show that Schockley's model[10] is applicable to these elemental semiconductors. We therefore assumed the following forms of α and β in $Si_{1-x}Ge_x$:

$$\alpha(E)=\alpha_0 e^{-E_\alpha/E(x)}, \tag{1}$$

and

$$\beta(E)=\beta_0 e^{-E_\beta/E(x)}, \tag{2}$$

where α_0 and β_0 (cm^{-1}) are constant prefactors and E_α and E_β (V/cm) are constants. In the depletion region of a p-i-n diode under large reverse bias, the electron multiplication factor M_n can be expressed as:[11]

$$1-\frac{1}{M_n}=\int_0^W \alpha(E)\exp\left\{-\int_0^x[\alpha(E)-\beta(E)]dx'\right\}dx, \tag{3}$$

where W is the width of the depletion region. A similar equation in terms of M_p can be written for pure hole injection. The electric field profile $E(x)$ is determined by solving the current continuity equation and Poisson equation simultaneously with the known carrier concentration profile in the i

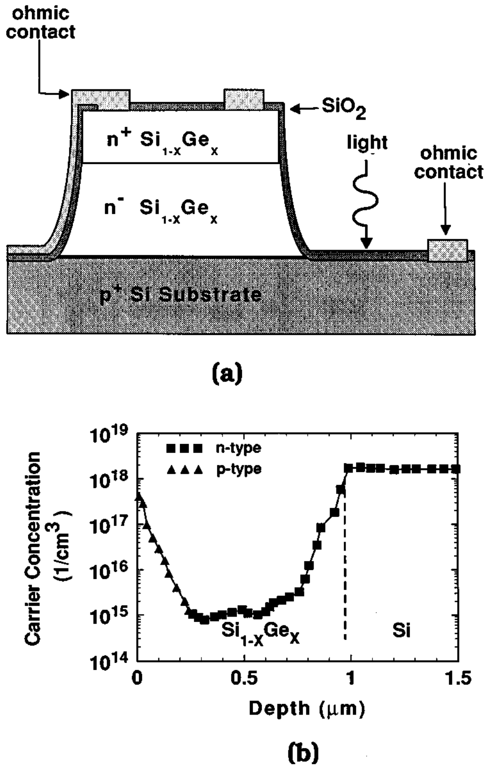

FIG. 1. (a) p^+ (Si)-n^-(SiGe)-n^+(SiGe) diode structure for pure electron injection, and (b) spreading resistance analysis data for the carrier concentration profile in a typical diode.

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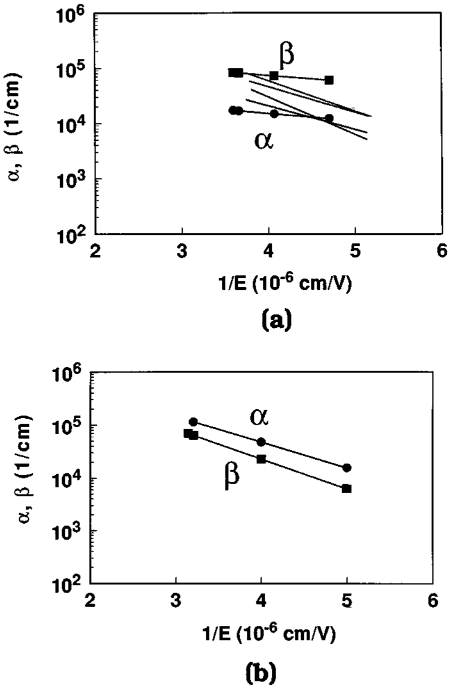

FIG. 2. (a) Measured impact ionization coefficients in Ge. The solid lines indicate previously published data (Refs. 5–7); (b) measured impact ionization coefficients in $Si_{0.69}Ge_{0.31}$.

region. Using Eqs. (1)–(3), one can deduce α_0, E_α, β_0, and E_β from the measured $M_n(E)$ or $M_p(E)$ plot by a numerical curve fitting technique.[12]

The temperature-dependent current–voltage characteristics of a p^+-i ($Si_{0.69}Ge_{0.31}$)-n^+ diode were measured and an increase of the breakdown voltage V_{BR} with lowering of temperature was observed. This result confirmed that avalanche multiplication is the dominant breakdown mechanism in these devices and that tunneling or the formation of microplasmas will not vitiate our results.

Figure 2(a) shows the results of measurements on a diode with a pure Ge i-region. The values of α and β are in fair agreement with published data for Ge.[5–7] This validates our measurement and analysis technique outlined above. Figure 2(b) depicts $\alpha(E)$ and $\beta(E)$ measured in $Si_{0.69}Ge_{0.31}$. The meaured β/α values as a function of x at $E=330$ kV/cm are listed in Table I and the coefficients themselves, at the same fixed value of E are shown in Fig. 3. The single most important feature in the data is that a crossover ($\beta/\alpha=1$) occurs between $x=0.4$ and $x=0.5$. It is stressed that the values of α and β being reported here may be in slight error due to the uncertainty in the curve fitting process. However, the trend of the ratio β/α is as expected and is the crux of this letter.

TABLE I. Measured values of β/α in $Si_{1-x}Ge_x$.

Composition (x)	β/α at $E=330$ kV/cm
0.00	0.1–0.5
0.08	0.3
0.30	0.6
0.68	3
1.00	1.5–4

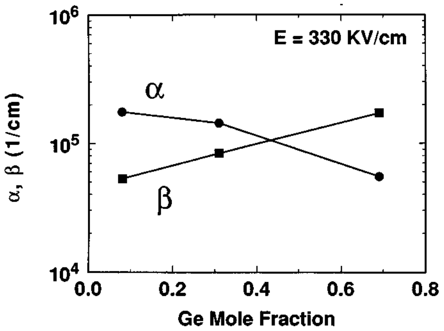

FIG. 3. Measured values of α and β as a function of Ge mole fraction in $Si_{1-x}Ge_x$ at $E=330$ kV/cm.

The measurements reported here have been made on relaxed $Si_{1-x}Ge_x$. Therefore, the misfit dislocation density in the active multiplication region is expected to be quite high (10^6–10^8 per cm^2). However, since we are measuring the properties of hot carriers, the effect of dislocations on the impact ionization process is probably small. Second, in the relaxed alloys, the degeneracy in the bands is still present and only changes in the band-gap and alloy scattering play dominant roles. Therefore, an increase in the value of α with x is not expected[8] or observed in our measurements. Finally, alloy clustering effects, which are known to modify the carrier multiplication process,[13] have not been accurately characterized in these alloys.

In conclusion, the electron (α) and hole (β) impact ionization coefficients in $Si_{1-x}Ge_x$ alloys have been measured. From the results we find that in Si-rich alloys, α is greater than β and in Ge-rich alloys, β is greater than α.

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