Impact ionization coefficients for electrons and holes in strained $In_{0.2}Ga_{0.8}As$ and $In_{0.15}Ga_{0.63}Al_{0.22}As$ channels embedded in $Al_{0.3}Ga_{0.7}As$

Y. C. Chen and P. K. Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109-2122

(Received 13 April 1992; accepted for publication 16 September 1992)

We have measured impact ionization coefficients, α and β, in 150 Å pseudomorphically strained materials for the first time. The measurements were made on specially designed lateral *p-i-n* diodes. α and β in lattice-matched GaAs layers are found to be lower than those in strained $In_{0.2}Ga_{0.8}As$ and higher than those in strained $In_{0.15}Ga_{0.63}Al_{0.22}As$. β is larger than α in all the samples. The results are discussed in terms of the changes in the band structure due to biaxial strain.

Measurements of impact ionization coefficients in different bulk and multilayered lattice-matched semiconductors have been reported in the literature.[1-3] Biaxial strain alters the band gap and band structure of the material, and is therefore expected to alter the impact ionization coefficients. However, no measurements of impact ionization coefficients in pseudomorphically strained semiconductors have been reported, except those made by one of us (PKB) and co-authors with InGaAs/GaAs strained multiquantum wells (MQW).[4] Conventionally, the measurement of impact ionization coefficients are made with *p-n* or *p-i-n* diodes in which carriers move in a 1–2-μm-thick active region in a direction perpendicular to the sample surface. Such devices cannot be used for measuring the ionization coefficients in pseudomorphically strained layers whose thickness must be smaller than the critical thickness. In this communication, we report the measurements of impact ionization coefficients of electrons and holes in pseudomorphically strained layers using specially designed and fabricated *lateral p-i-n* diodes.

The experimental samples, shown in Fig. 1, were grown by molecular beam epitaxy (MBE). The different channel materials that were investigated are: (1) Strained $In_{0.2}Ga_{0.8}As$, which has band gap smaller than that of GaAs, (2) strained $In_{0.15}Ga_{0.63}Al_{0.22}As$, which has a band gap about the same as that of GaAs, and (3) lattice-matched GaAs. Background carrier concentration was 3.5×10^{14} cm^{-3}, as measured from a bulk GaAs layer grown at the same time when the experimental samples were grown. Shown in Fig. 1 is a schematic of the lateral *p-i-n* diodes designed and fabricated for pure hole injection. The slit on top allows photoexcitation and generation of electron-hole pairs in the n^+ region. Under reverse bias, the photogenerated electrons are swept out of the *n*-type ohmic contact and the holes are injected into the channel through diffusion, resulting in single carrier injection. The undoped region is completely covered by an Au-SiO_2 bilayer to prevent any photogeneration of free carriers in this area. The thickness of the SiO_2 layer is 0.6 μm. The channel width is 150 μm.

Impact ionization measurements were made by monitoring the photocurrent multiplication as a function of reverse bias. The multiplication coefficients, M_n (M_p), for pure electron (hole) injection were measured from devices with open slits in the p^+ region (n^+ region). Shown in Fig. 2 are the measured photocurrent multiplication factors due to pure hole and pure electron injection in the lateral *p-i-n* diodes of different channel materials.

We have deduced the impact ionization coefficients, α and β, from the measured current multiplication factors. Assuming that the electric field along the undoped channel is constant and that pure electron (hole) injection from one end of the channel can be obtained, we can obtain the following relations between impact ionization coefficients and current multiplication factors by integration of Eqs. (27) and (28) in Ref. 5,

$$1-\frac{1}{M_p}=\frac{\beta}{\alpha-\beta}\,(e^{(\alpha-\beta)\omega}-1)\,, \tag{1}$$

$$1-\frac{1}{M_n}=\frac{\alpha}{\beta-\alpha}\,(e^{(\beta-\alpha)\omega}-1)\,. \tag{2}$$

We also assume the following forms for α and β:[6]

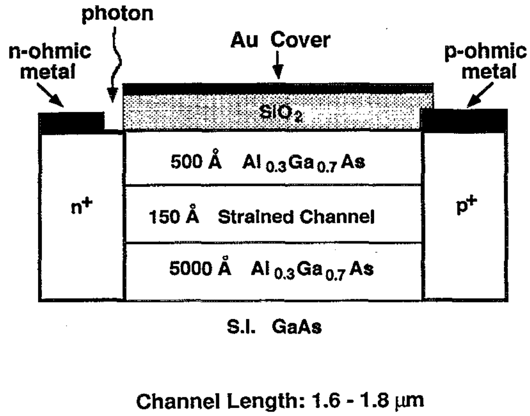

FIG. 1. Schematic of the lateral *p-i-n* diodes designed and fabricated for pure hole injection.

0021-8979/93/010465-03$06.00

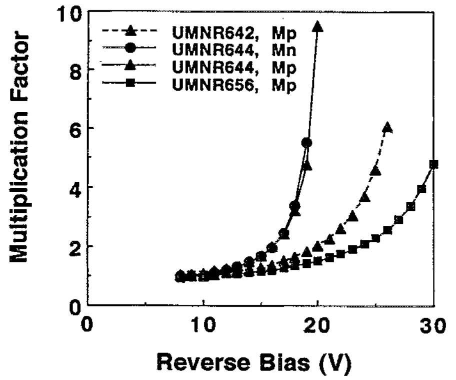

FIG. 2. Measured multiplication factors for pure electron and hole (M_n and M_p, respectively) injection. The channels of sample UMNR642, 644, and 656 are GaAs, $In_{0.2}Ga_{0.8}As$, and $In_{0.15}Ga_{0.63}Al_{0.22}As$, respectively.

TABLE I. Constants for ionization coefficients of electrons, $\alpha = \alpha_0 \exp(-E_\alpha/E)$, and holes, $\beta=\beta_0 \exp(E_\beta/E)$, deduced from photocurrent multiplication factors.

Channel device type	α_0 (10^4 cm^{-1})	E_α (10^5 V/cm)	β_0 (10^4 cm^{-1})	E_β (10^5 V/cm)
GaAs (hole injec.)	3.82	3.80	4.50	3.10
$In_{0.15}Ga_{0.63}Al_{0.22}As$ (hole injec.)	3.19	4.03	3.92	3.25
$In_{0.2}Ga_{0.8}As$ (hole injec.)	5.90	3.00	6.80	3.02
$In_{0.2}Ga_{0.8}As$ (electron injec.)	5.50	3.00	6.50	3.04

$$\alpha=\alpha_0 e^{-E_\alpha/E}, \tag{3}$$

$$\beta=\beta_0 e^{-E_\beta/E}, \tag{4}$$

where α_0 and β_0 (cm^{-1}) are constant prefactors and E_α and E_β (V/cm) are constants.

Using Eqs. (1)–(4), one can deduce α_0, E_α, β_0, and E_β from a single $M_p(E)$ or $M_n(E)$ curve by a numerical curve-fitting technique. α and β, so calculated from the data of Fig. 2, are plotted in Fig. 3 and the value of the constants obtained from such fitting are listed in Table I. The ionization coefficients obtained from pure-electron-injected devices are fairly consistent with those obtained from pure-hole-injected devices. One can see that both α and β in the GaAs channel are lower than those in the $In_{0.2}Ga_{0.8}As$ channel and higher than those in the strained $In_{0.15}Ga_{0.63}Al_{0.22}As$ channel. We believe that the variations are caused by changes in band gap and hole effective mass in the different channel materials. When considering the problem of impact ionization in semiconductors, it is often assumed[7] that there exists a well-defined threshold energy E_T such that an incident charge carrier will have a probability to produce an electron-hole pair by impact ionization when its energy is larger than E_T. For spherical parabolic bands, E_T is given by

$$E_T=\left(\frac{1+2\mu}{1+\mu}\right) E_g, \tag{5}$$

where E_g is the band gap of the semiconductor and $\mu=m_e'/m_h^*$. Keldysh[8] has given an analytic approximation for the impact ionization rate, which is given by

$$\frac{1}{\tau_i(E)}=\frac{P}{\tau(E_T)}\left(\frac{E-E_T}{E_T}\right)^2, \tag{6}$$

where $1/\tau_i(E)$ is the ionization rate, $1/\tau(E_T)$ is the phonon scattering rate at $E=E_T$, and P is a constant. We can see from Eqs. (5) and (6) that (1) for fixed band gap, a smaller hole effective mass gives a larger E_T, and thus a lower ionization rate, and that (2) for fixed carriers masses, a smaller band gap gives a smaller E_T, and consequently a larger ionization rate. For the strained $In_{0.15}Ga_{0.63}Al_{0.22}As$ channel, E_g remains the same but m_h^* decreases, as compared to GaAs, resulting in an increase in E_T and a decrease in impact ionization rates. For the strained $In_{0.2}Ga_{0.8}As$ channel, although m_h^* decreases, the significantly reduced band gap leads to a smaller E_T. This results in increased impact ionization coefficients. Eq. (5) is a very rough approximation for E_T, since bands are very far from parabolic at high energy. However, Keom *et al.*[9] have made much sophisticated calculations using (1) 6-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian for valence-band states, (2) a tight-binding method for conduction-band states, and (3) a perturbation theory for the transition rates. Their results also show that excess In can reduce the threshold ionization energy and that if compressive strain is introduced without altering the band gap the threshold energy is increased. These calculations agree with our experimental results. The reduced ionization coefficients in the $In_{0.15}Ga_{0.63}Al_{0.22}As$ channel might be also partly due to the increased random alloy scattering caused by the ternary material. One may also notice that $\beta>\alpha$ for all the samples.

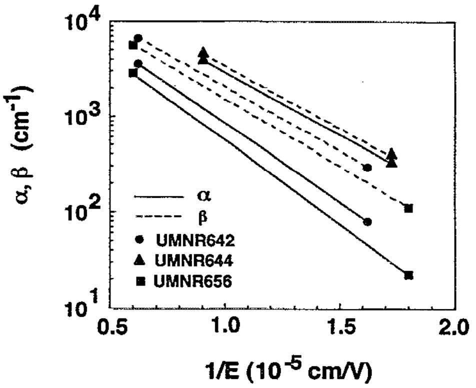

FIG. 3. Ionization coefficients deduced from the multiplication factors. The channels of sample UMNR642, 644, and 656 are GaAs, $In_{0.2}Ga_{0.8}As$, and $In_{0.15}Ga_{0.63}Al_{0.22}As$, respectively.

This work is supported by the Office of Naval Research under Grant N00019-89-J1519. The authors acknowledge useful discussions with Professor J. Singh.

[1] See, for example, F. Capasso, in *Semiconductor and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1985), Vol. 22, p. 1.

[2] F.-Y. Juang, U. Das, Y. Nashimoto, and P. K. Bhattacharya, Appl. Phys. Lett. **47**, 972 (1985).

[3] P. K. Bhattacharya, Y. Zebda, and J. Singh, Appl. Phys. Lett. **58**, 2791 (1991).

[4] P. K. Bhattacharya, U. Das, F.-Y. Juang, Y. Nashimoto, and S. Dhar, Solid-State Electron. **29**, 261 (1986).

[5] G. E. Stillman and C. M. Wolfe, in *Semiconductor and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1977), Vol. 12, p. 291.

[6] W. Shockley, Solid-State Electron. **2**, 35 (1961).

[7] S. McKenzie and M. G. Burt, J. Phys. C **19**, 1959 (1986).

[8] L. V. Keldysh, Sov. Phys. JETP **37**, 509 (1960).

[9] Y. Keom, V. Sankaran, and J. Singh, *Proceedings of the 18th International Symposium on GaAs and Related Compounds*, Seattle, Washington, September, 1991 (IOP Publishing Ltd.), pp. 517–522.