nating from the impurities commonly found in GaAs, i.e., C, O, Si, S, can reasonably be ruled out by a careful comparison between the concentrations of these impurities and of EL2 and from their variations between the tail and the head of ingots. We are then left to the conclusion that $X = As_i$. This conclusion based on qualitative arguments is verified by direct observations of the As_i mobility, deduced from extensive studies of electron irradiation induced complexes defect. This mobility is found to occur exactly in the temperature range where we observe the regeneration of As_{Ga}^{∇} from As_{Ga}^{*} through the mobility of X. These observations are (i) absorption measurements of local modes of vibration have shown[5] that irradiation induced C_{As}-As_i complexes dissociate thermally at 130 °C and lead to the regeneration of C_{As} acceptors[6]; since substitutional C is stable at these temperatures, the dissociation can only occur through As_i mobility; (ii) the thermal dissociation of B-As_i pairs as well as the recombination of V_{As}-As_i pairs also occurs around 200 °C.[7] Another evidence, which will be described elsewhere, can be deduced from the formation of EL2 defects following electron irradiation at ~ 300 °C (temperature at which the created As_i are mobile).

In conclusion, we have provided a set of complementary observations which strongly suggest that EL2 is a complex formed by an antisite As_{Ga} and a defect X in agreement with one of the recent suggestions of Ikoma *et al.*[8] Having observed the mobility of X and using data concerning irradiation induced defects, we have been able to conclude that X is the interstitial As. We shall show elsewhere (using a simple tight binding treatment) that this identification is in agreement with the metastable character of EL2, the two different configurations, i.e., the different positions that As_i can take near the antisite, being driven by the relative charge states of As_{Ga} and As_i through a Coulombic repulsion or attraction, in agreement with Levinson's model.[9] It is also easy to see that this identification allows one to understand fully the thermal behavior of EL2 as well as the growth conditions in which it is created. Finally, the other interpretation of these observations, namely that EL2 is the isolated antisite and As_{Ga}^{*}, produced by irradiation, the complex involving As_i is ruled out quite simply since electron irradiation can produce a concentration of As_{Ga}^{*} defects very large compared to the initial concentration of EL2 defects.

We are very grateful to M. Bonnet (Laboratoire Central de Recherches/Thomson–CSF) who kindly has grown several ingots specially for this study, and to D. Deresme for his technical assistance. This work has been supported by Centre National d'Etudes des Télécommunications (contract n° 84.6B007.90245) and Direction des Recherches et Etudes Techniques (contract n° 83.34.050.4707501).

[1] A. L. Lin, E. Omekanovski, and R. H. Bube, J. Appl. Phys. **47**, 1852 (1976).
[2] For a recent review, see, S. Makram-Ebeid, P. Langlade, and G. M. Martin in *Semi-Insulating III-V Materials* (Shiva, England, 1984), p. 184.
[3] K. Elliot, R. T. Chen, S. G. Greenbaum, and R. J. Wagner, Appl. Phys. Lett. **44**, 907 (1984).
[4] M. Bäumler, U. Kaufmann, and J. Windscheif, Appl. Phys. Lett. **46**, 781 (1985).
[5] H. J. von Bardeleben and J. C. Bourgoin, J. Appl. Phys. **58**, 1041 (1985).
[6] R. C. Newman and J. Woodhead, J. Phys. C (to be published).
[7] For a recent review, see D. Pons and J. C. Bourgoin, J. Phys. C **18**, 3839 (1985).
[8] T. Ikoma, M. Taniquehi, and Y. Maahizuki, Inst. Phys. Conf. Ser. 74 (Adam Hilger, Bristol, 1985), p. 65.
[9] M. Levinson, Phys. Rev. B **28**, 3660 (1983).

Electron and hole impact ionization coefficients in GaAs-$Al_xGa_{1-x}As$ superlattices

F-Y. Juang, U. Das, Y. Nashimoto,[a] and P. K. Bhattacharya
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, Michigan 48109

(Received 17 June 1985; accepted for publication 18 August 1985)

Electron and hole multiplication and impact ionization coefficients have been measured with pure carrier injection in p^+-n^--n^+ and p^+-n diodes grown by molecular beam epitaxy. Values of the electron and hole ionization coefficient ratio $\alpha/\beta = 2$–5 are measured for superlattices with well width $L_z \geqslant 100$ Å and $\alpha/\beta > 10$ is measured in a graded band-gap superlattice with a total well and barrier width $L_B + L_Z = 120$ Å. The ratio decreases and becomes less than unity for smaller well sizes. This is caused by an increase in $\beta(E)$ while $\alpha(E)$ remains fairly constant. The results have been interpreted by considering varying hole confinement and scattering in the coupled quantum wells.

It has been predicted that GaAs-$Al_xGa_{1-x}As$ superlattices can exhibit enhanced ionization coefficient ratios α/β.[1,2] This makes them attractive materials for fabricating low-noise avalanche photodiodes[3] and transit-time microwave devices. Reported measurements of α/β (Refs. 1, 2) have only been made on GaAs-$Al_xGa_{1-x}As$ multilayered

[a] On leave from NEC Corporation, Kawasaki, Japan.

TABLE I. Superlattice description and comparison of impact ionization coefficients $E_M^{-1} = 3.5\times 10^{-6}$ (cm V^{-1}).

Sample	L_B (Å)	L_Z (Å)	α ($\times 10^3$) cm^{-1}	β ($\times 10^3$) cm^{-1}
UM 171	GaAs		2.2	0.98
UM 149	Graded bandgap		4.6	0.34
UM 82	145	87	2.5	3.5
UM 152	154	33	1.66	1.62
UM 150	56	34	3.0	10.5
UM 92	$Al_{0.4}Ga_{0.6}As$		0.25	0.89

structures with large well and barrier widths (L_z and L_B) and, to the best of our knowledge, no such data exist for superlattices with L_Z and $L_B \sim 30$–100 Å. An accurate knowledge of the ionization coefficients is necessary both for designing low-noise avalanche photodiodes and for understanding the physical mechanisms operative in superlattices at or near breakdown conditions.

p^+-n^--n^+ and p^+-n abrupt junctions with superlattice absorption regions were grown by molecular beam epitaxy on n^+ substrates. A 1-μm GaAs buffer layer doped to $n = 2\times 10^{18}$ cm^{-3} is first grown. This is followed by the n-type GaAs-$Al_xGa_{1-x}As$ superlattice region with $x = 0.4$ and is typically 2 μm thick. This is followed by a 3-μm Be-doped $Al_{0.4}Ga_{0.6}As$ layer with $p = 3\times 10^{18}$ cm^{-3} and a 100-Å Be-doped GaAs contact layer with $p = 3\times 10^{18}$ cm^{-3}. In some cases the top p^+-$Al_{0.4}Ga_{0.6}As$ layer was eliminated and was replaced by a 2–3-μm-thick p^+-GaAs layer. Alloyed Ti/Au and Au/Ge/Ni ohmic contacts were made on the p and n sides of the diode, respectively. The contacts were annealed at 450 °C for 1 min. L_B and L_Z in the superlattice vary from $\sim$30 to 160 Å. In one structure L_B and L_z were progressively varied with $L_B + L_Z = 120$ Å to get a graded band-gap superlattice. Such structures have led to improved performance of photodetectors.[4] The quality of the heterointerfaces was monitored by low-temperature high-resolution photoluminescence measurements and only samples exhibiting high exciton recombination intensities and linewidths $\sim$0.5–5.0 meV were used. Structure configurations are described in Table I. Measurements were also made on bulk GaAs and $Al_{0.4}Ga_{0.6}As$ for calibration purposes.

Mesa diodes with 250 μm diameter were delineated by standard photolithography. Large-area backside and annular top ohmic contacts were formed by evaporation and alloying. The reverse breakdown voltage V_B in the one-sided junctions is in the range of 50–100 V and the dark current at $0.5V_B$ is typically in the range 10^{-10}–10^{-11} A. The carrier concentration in the n-superlattice region is derived from capacitance-voltage data. Isolated holes were etched in the substrate beneath some devices to enable injection of holes from the n^+ contact region during measurements.

Electron and hole photocurrents were generated by illuminating the diodes with a chopped He-Ne 5-μm-diam laser ($\lambda = 6328$ Å) beam. The photomultiplication as a function of reverse bias was monitored with a lock-in amplifier. Pure hole injection was effected in two ways. In the first technique the laser spot was focused on the etched n^+ layer at the edge of the mesa and was moved laterally until the measured multiplication was constant. In the second technique, the diode was illuminated through the hole etched into the n^+ substrate. Electron-initiated multiplication was achieved by illuminating the p^+ layer on the top of the mesa structure. To obtain the electron and hole multiplication factors, appropriate stable values of the photocurrent at low bias values were considered.

Multiplication factors measured with pure electron and hole injection in diodes with constant and graded band-gap superlattice absorption regions are shown in Figs. 1(a) and 1(b), respectively. The doping in the superlattice regions of all the devices studied is uniform at levels of $(1$–$3)\times 10^{15}$ cm^{-3}. Since L_B, L_Z are both much smaller than the usual values of α^{-1}, β^{-1} measured in these wide band-gap semiconductors, the relationships between the multiplication factors and the impact ionization coefficients applicable for bulk materials can be assumed to be valid for superlattices. We have therefore used the equations[5]

$$\alpha(E) = \frac{1}{W}\frac{M_n - 1}{M_n - M_p}\ln\left(\frac{M_n}{M_p}\right)$$

$$\beta(E) = \frac{1}{W}\frac{M_p - 1}{M_p - M_n}\ln\left(\frac{M_p}{M_n}\right) \tag{1}$$

which are valid for a p-i-n diode. Here W is the width of the n^- region. In some cases, depending on doping, the equations for a p^+-n diode with punchthrough conditions[5] had to be used.

Figure 2 depicts the electron and hole impact ionization coefficients measured in some of the superlattice diodes. It is apparent that the values of $\alpha(E)$ remain fairly constant, while the values of $\beta(E)$ are strongly dependent on superlattice dimensions. The α and β values at $E^{-1} = 3.5\times 10^{-6}$ cm V^{-1}

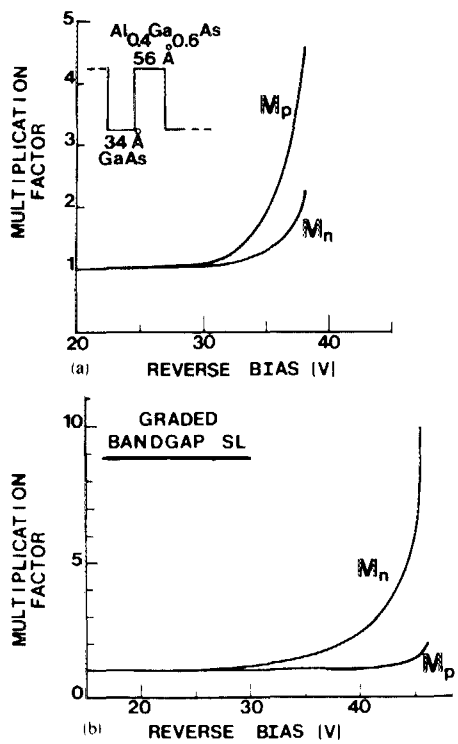

FIG. 1. Electron and hole multiplication measured in (a) constant band-gap superlattice with $L_z = 34$ Å, $L_B = 56$ Å under pure injection conditions and (b) graded band-gap superlattice (period = 120 Å).

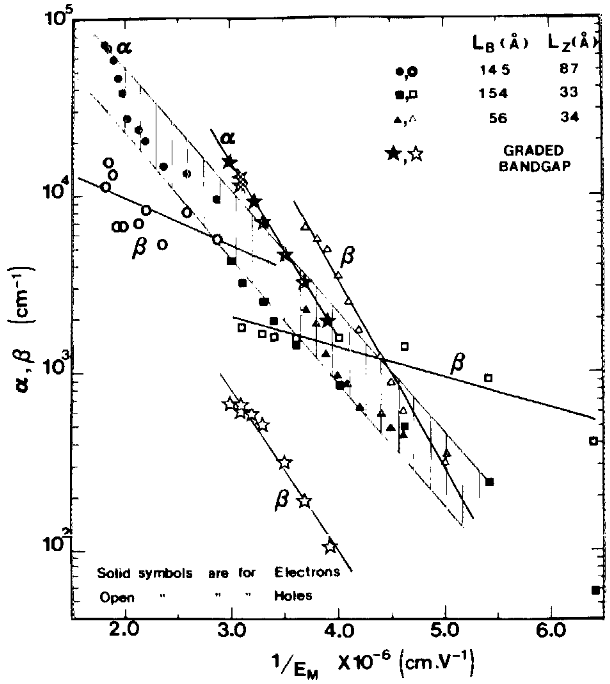

FIG. 2. Measured values of $\alpha(E)$ and $\beta(E)$ in superlattice avalanche photodiodes. The shaded area represents an average invariant value of α.

are also listed in Table I for the different materials measured in the course of this study. The values for GaAs are in good agreement with previously reported values.[6,7]

It may be assumed at the outset that in all the superlattice structures being reported here, $L_B < 160$ Å and therefore the wells are quantum-mechanically coupled to each other. In such quasi-two-dimensional systems the carrier-phonon interactions and scatterings are enhanced.[8] The measured data can be explained reasonably well by considering carrier confinement and scattering in the quantum wells. From Table I and Fig. 2 it is obvious that, within limits of experimental error, α remains fairly constant with a value similar to that measured in bulk GaAs. The electrons with smaller effective mass are not truly confined in wells with $L_B < 160$ Å and have fairly high energies relative to the GaAs conduction-band edge. Therefore, electron scattering in the quantum wells is very limited and the measured values of α reflect, within limits of experimental error, bulklike behavior. The holes, on the other hand, have much larger mass and smaller path lengths for scattering. Therefore, it is expected that hole multiplication will be dependent on hole confinement and scattering in the quantum wells, which in turn depend on the well widths. Furthermore, the coupling between the wells will also alter the degree of confinement. As expected, we see that at higher fields values of β for the SL in sample UM 150 are higher than those for the superlattice in sample UM 82. For the same well size, as L_B is reduced, it is expected that the hole confinement will increase, at least for low fields. This is indeed the case, as seen by comparing the samples with $L_z \sim 34$ Å, but $L_B = 154$ and 56 Å (samples 150 and 152). Moreover, for small L_B and L_z, the superlattice probably behaves more like the bulk alloy $Al_xGa_{1-x}As$. Therefore, for certain field values, $\beta > \alpha$, as measured in the alloy in this study and by other authors.[9]

In the graded band-gap superlattice with a period of 120 Å, the value of $\beta(E)$ is lower than those in the other samples since the motion of holes is opposed by the quasi-electric field. The general trend of α/β in the superlattices can be summarized as follows. The ratio has values between 2–5 in superlattices with large wells. As the well size is reduced α/β tends toward values < 1. In the graded band-gap superlattice, $\alpha/\beta > 10$ is measured.

An attempt was made to calculate the α/β ratio using the common phonon model,[10] from which

$$\frac{\beta}{\alpha} = \left(\frac{E_i^e}{E_i^h}\right)^2 \exp\left\{x_h\left[\left(\frac{E_i^e}{E_i^h}\right)^{3/2} - 1\right]\right\}, \tag{2}$$

where $E_i^{e,h}$ are the electron and hole threshold ionization energies, $x_h = E_i^h/e\mathscr{E}\lambda_h$, and λ_h is the hole-phonon scattering length. However, values of $\alpha/\beta > 1$ are obtained for $Al_{0.4}Ga_{0.6}As$ with E_i^e and $E_i^h = 2.0$ eV and 2.3 eV, respectively.[9] We feel that the discrepancies are due to erroneous parameters, and in particular the threshold ionization energies.

In conclusion, we have measured the ratio of the impact ionization coefficients in coupled quantum well systems for the first time. In superlattices with large wells and barriers $\alpha/\beta \sim 2$–5 are measured at high fields. As the well size is reduced, α approaches a value similar to that in GaAs, and β increases. Our data suggest that the rate of hole scattering and impact ionization is greatly dependent on hole quantum well size. This parameter primarily decides the α/β value.

Discussions with Dr. T. P. Pearsall are gratefully acknowledged. The work is supported by NASA, Langley Research Center under grant NAG-1-555. Partial support by a grant from Instruments S. A., Riber Division is also acknowledged.

[1]F. Capasso, W. T. Tsang, A. L. Hutchinson, and G. F. Williams, Appl. Phys. Lett. **40**, 38 (1982).
[2]F. Capasso, W. T. Tsang, and G. F. Williams, IEEE Trans. Electron Devices **ED-30**, 381 (1983).
[3]R. J. McIntyre, IEEE Trans. Electron Devices **ED-13**, 164 (1966)..
[4]F. Capasso, J. Vac. Sci. Technol. B **1**, 457, (1983).
[5]G. E. Stillman and C. M. Wolfe, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1977), Vol. 12, pp. 291–393.
[6]G. E. Bulman, V. M. Robbins, K. F. Brennan, K. Hess, and G. E. Stillman, IEEE Electron Device Lett. **EDL-4**, 181 (1983).
[7]T. P. Pearsall, Solid State Electron. **21**, 297 (1978).
[8]N. Holonyak, Jr., R. M. Kolbas, R. D. Dupuis, and P. D. Dapkus, IEEE J. Quantum Electron. **QE-16**, 170 (1980).
[9]J. P. R. David, J. S. Marsland, H. Y. Hall, G. Hill, N. J. Mason, M. A. Pate, J. S. Roberts, P. N. Robson, J. E. Sitch, and R. C. Woods, presented at the Eleventh International Symposium on Gallium Arsenide and Related Compounds, Biarritz, France 1984, Inst. Phys. Conf. Ser. **74**, 247 (1985).
[10]B. K. Ridley, J. Phys. C **16**, 4733 (1983).