Electron and hole impact ionization coefficients in GaAs/$Al_{0.45}Ga_{0.55}As$/$Al_{0.3}Ga_{0.7}As$ coupled well systems

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We have measured electron and hole multiplication factors and impact ionization coefficients in 550 Å GaAs/500 Å $Al_{0.3}Ga_{0.7}As$ quantum wells with an intermediate $Al_{0.45}Ga_{0.55}As$ barrier (50 and 100 Å) inserted in the well region. It is seen that while the measured value of $\alpha(E)$ is insensitive to the position of the intermediate barrier in the well, the value of $\beta(E)$ is very sensitive. The value of α/β varies from less than unity to 5, depending on the position of this barrier. These results suggest that hole confinement and scattering play a major role in making the value of α/β greater than unity in these multilayered structures.

After the first prediction of enhancement of α/β in GaAs/AlGaAs multiquantum wells by Chin *et al.*,[1] experimental verification was provided by Capasso and co-workers,[2,3] who extended the concept to a staircase superlattice. More recently, Juang *et al.*[4] systematically measured the electron and hole impact ionization coefficients in a series of GaAs/AlGaAs multiquantum wells and superlattices with varying well and barrier parameters. It was observed that while in superlattices with thin ($\leqslant$100 Å) wells and barriers, there was hardly any enhancement in α/β, a large enhancement could be measured for well and barrier sizes $\sim$500 Å. It was also observed by Juang *et al.*[4] that the measured value of α was fairly insensitive to the quantum well parameters. On the other hand, the value of β was very much dependent on small changes in the well and the barrier dimensions, and it was this change that produced a variation in the value of α/β.

It is obviously important to understand the mechanism of enhancement of the value of α/β. In the staircase superlattice this is easy to understand in terms of the band lineup; electrons can impact ionize at each step, while the holes do not. This explanation may not be true for square wells $\sim$500 Å, where $\alpha/\beta \sim 10$ has also been measured. According to Capasso,[2,3] the enhancement of α/β in this structure also results from a periodic lowering of the threshold ionization energy of the electrons as they traverse an AlGaAs barrier and reach a GaAs well. This argument would be valid if ΔE_c:ΔE_v were equal to 85:15 and not 60:40, as established more recently. Furthermore, this explanation, if valid, would suggest that the enhancement in α/β should be due to an increase in the value of α. Experimentally, it is seen that the increase occurs due to the lowering of β. Therefore, other mechanisms need to be invoked in order to explain the observed increase in α/β for large wells and barriers.

In order to establish the role of the well widths in determining the values of α and β, measurements have been made in this study on MQW structure with $\sim$ 500 Å wells and barriers, with an additional thin AlGaAs barrier in the well regions. In what follows, the data obtained from these measurements are described and discussed.

Photodiode structures with $\sim$2 μm undoped MQW multiplying regions were grown on Si-doped n^+ (100) GaAs substrates by MBE. The multiplying region consists of a GaAs/$Al_{0.3}Ga_{0.7}As$ MQW with well/barrier dimensions of 550/500 Å. A thin barrier of $Al_{0.45}Ga_{0.55}As$, with different thicknesses and locations, is added in the well region to study its effect on the impact ionization and to understand the mechanism of the enhancement of the impact ionization rates. Three structures were grown: type I has an intermediate barrier of thickness 50 Å located closer to one end of the well, type II has an intermediate barrier with the same thickness but positioned at the other end of the well, and type III has the thin barrier with a thickness of 100 Å located in the same position as the second one. The conduction band profiles corresponding to these three configurations are shown in Fig. 1. It should be noted that the MQW region immediately following the 2 μm n^+ GaAs layer first grown on the substrate is grown as multiple periods of the structures shown in Fig. 1, from left to right. A 2-μm- thick Be-doped (2×10^{18} cm^{-3}) GaAs p^+ layer is grown on top of the MQW region for pure electron injection with intrinsic photoexcitation. Mesa diodes with 500 μm diameter were delineated by standard photolithography and chemical etching. A backside hole under the diode was formed by selective etching. The dc characteristic of the diodes were measured, and they exhibit a reverse breakdown voltage of typically 65 V. The reverse leakage current was 10–50 nA at 90% of the breakdown voltage, which makes these devices suitable for the impact ionization coefficient measurements.

The carrier multiplication and impact ionization coefficients were measured using a 6328 Å He–Ne laser focused through a 60$\times$ microscope objective lens onto the sample. A beamsplitter and a chopper were inserted between the laser and the lens to allow phase-sensitive detection. Pure hole injection was achieved by illuminating the diode through the hole etched into the n^+ substrate. Electron

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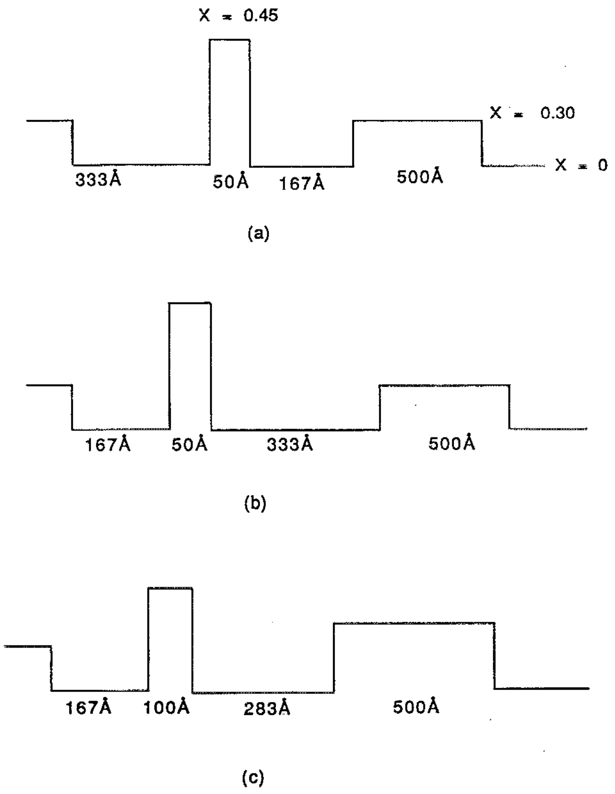

FIG. 1. Three GaAs/$Al_{0.3}Ga_{0.7}As$ multiquantum well configurations having a thin barrier inside the GaAs well: (a) (type I) GaAs(167 Å)/$Al_{0.45}Ga_{0.55}$(50 Å)/GaAs(333 Å); (b) (type II) GaAs(330 Å)/$Al_{0.45}Ga_{0.55}As$(50 Å)/GaAs(167 Å); (c) (type III) GaAs(283 Å)/$Al_{0.45}Ga_{0.55}As$ (100 Å)/GaAs(167 Å).

initiated multiplication was achieved by illuminating the p^+ layer on top of the mesa structure. To derive the electron and hole multiplication factors, appropriate stable values of the photocurrent at low bias were used as reference. The multiplication coefficients M_n and M_p, for electrons and holes, for the three configurations were calculated and are shown in Fig. 2. From the measured values of electron and hole multiplication coefficients, the impact ionization coefficients α and β were calculated by using the pin diode formulation.[5] The calculated impact ionization coefficients for the three MQW configurations are shown in Fig. 3.

The value of electron impact ionization coefficients for the three structures can be approximately fitted by the equation:

$$\alpha(E)=1.23\times10^{7}\ \exp(-2.73\times10^{8}/E)\ \mathrm{cm}^{-1}. \quad (1)$$

The hole impact ionization coefficients of the three structures were fitted separately, because these values are different in the different structures. They are

$$\beta(E)=1.05\times10^{5}\exp(-1.26\times10^{6}/E)\ \mathrm{cm}^{1}\ \text{(type I)}, \quad (2)$$

$$\beta(E)=1.37\times10^{6}\exp(-2.18\times10^{6}/E)\ \mathrm{cm}^{1}\ \text{(type II)}, \quad (3)$$

$$\beta(E)=6.65\times10^{4}\exp(-1.52\times10^{6}/E)\ \mathrm{cm}^{1}\ \text{(type III)}. \quad (4)$$

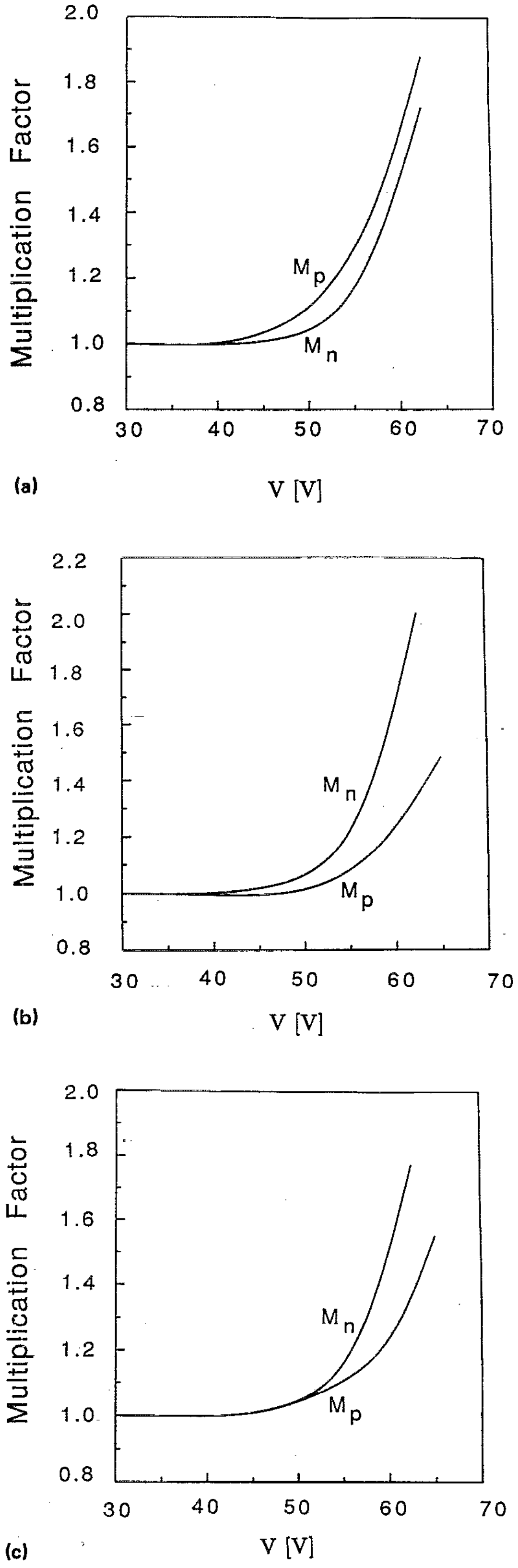

FIG. 2. Measured electron and hole multiplication coefficient for (a) type I, (b) type II, and (c) type III MQW.

For the type I well structure the electron impact ionization coefficient $\alpha(E)$ is smaller than the hole impact ionization coefficient $\beta(E)$ in the measured bias range, and

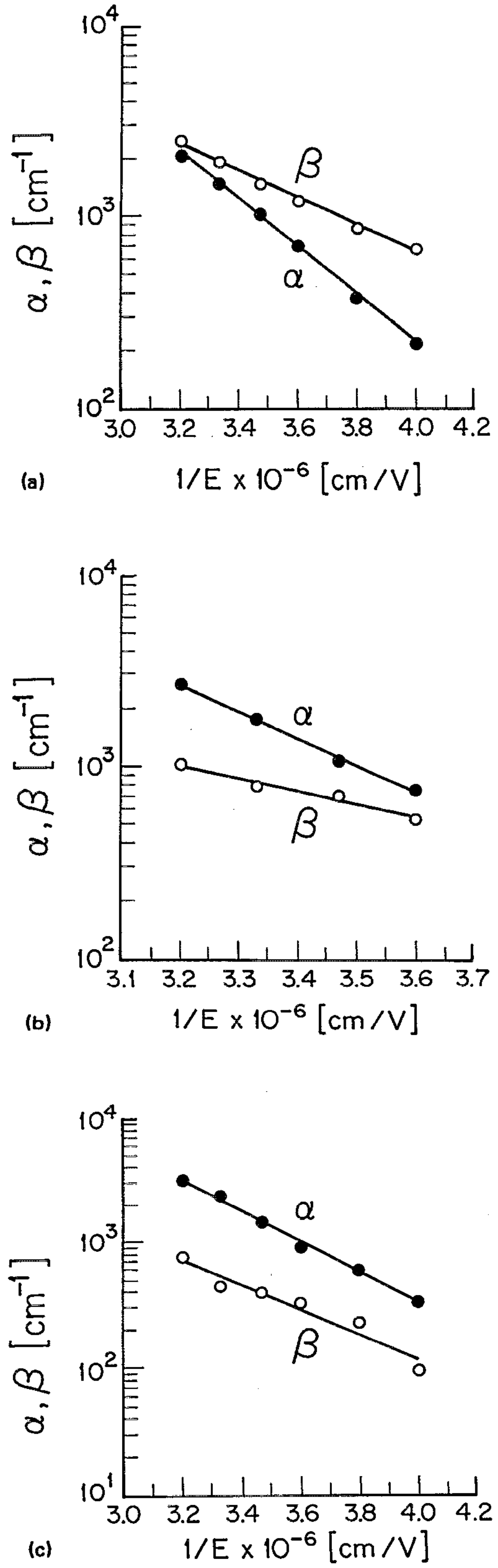

FIG. 3. Measured electron and hole impact ionization coefficients for (a) type I, (b) type II, and (c) type III MQW.

the ratio of β/α varies between 1 and 3. For the type II well structure, α is larger than β, and the ratio of α/β varies in the range 1–3. For the type III well structure, α is again larger than β and the ratio of α/β varies between 2 to 5. It should be noticed that for the three different structures the value of $\alpha(E)$ is almost the same, within limits of experimental error. This is because the electrons have a smaller effective mass, and are therefore not truly confined in the well. Electron scattering in the well is very limited and the measured values of α reflect this behavior. On the other hand, the value of $\beta(E)$ varies from one structure to another. It is seen that β has its largest value for the type I well structure, where the holes have smaller confinement. This is because holes which are injected from the n^+ layer encounter a wider well (333 Å) followed by a thin barrier (50 Å). The smallest value of β is found in the type III well structure, where the holes have more confinement because they face a smaller well size (167 Å) followed by a thicker barrier (100 Å) upon injection. From these results it is apparent that the electron impact ionization coefficients are not affected by the thin AlGaAs barrier inside the well, while the hole impact ionization coefficients are affected by the barrier, its position, and its thickness variation. Preliminary Monte Carlo results[6] show that the main reason for the lowering of hole multiplication is that after a hole has impact ionized, the two resulting holes have energies very close to the top of the valence band in the well and have difficulty in overcoming the barrier placed inside the well. On the other hand, the electrons have a higher energy after impact ionization, and also being lighter particles do not feel the presence of the barrier as much. The results indirectly support a larger valence band offset than a 85:15 (ΔE_c:ΔE_v) lineup. Finally, we conclude from this measurement that α/β can be altered by varying the quantum well design, and the hole confinement and scattering in the wells play a dominant role in altering the ionization coefficient ratio.

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