

## Electron Wave Reflection by Multi-Quantum Barrier (MQB)

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For the purpose of experimentally demonstrating the enhancement of electron wave reflection by a multi-quantum barrier (MQB), we have fabricated two types of n-GaAs/i-barrier/n-GaAs tunneling diodes with a bulk  $Al_xGa_{1-x}As$  barrier and an  $Al_xGa_{1-x}As/GaAs$  MQB. The measured current-voltage characteristic at 77 K is well understood by a virtually increased potential barrier height and electrons are well reflected by the MQB.

### 1. Introduction

A multi-quantum barrier (MQB)<sup>1), 2)</sup> was proposed to enhance the carrier confinement in semiconductor lasers by virtually increasing the potential barrier height using the interference of the reflected electron waves at the boundaries of stacked superlattices. It was theoretically shown that the MQB was very effective for short wavelength AlGaInP visible lasers by optimizing its parameters and by modifying its structure<sup>3)-5)</sup>. In our recent study, we have demonstrated the MQB effect by a photoluminescence experiment<sup>6)</sup>. Kishino et. al. reported a high characteristic temperature  $T_0$  by introducing the MQB into superlattice cladding layer of a 660-nm-range GaInP/AlInP laser<sup>7)</sup>. However, in these experiments, the direct observation of the electron wave confinement by the MQB was not confirmed, and the actual barrier height enhanced by the MQB has not been discussed yet.

In this study, to confirm the enhancement of carrier confinement effect by the MQB experimentally and quantitatively, we have employed the

n-i-n tunneling diode method<sup>8)</sup> and evaluated their current-voltage (I-V) characteristics.

### 2. Experiment

Two types of n-GaAs/i-barrier/n-GaAs tunneling diodes shown in Fig. 1 were fabricated on an n<sup>+</sup>-GaAs substrate by molecular beam epitaxy (MBE). We first grew a 1  $\mu$  m thick Si-doped n-GaAs ( $N_d = 1.8 \times 10^{18} \text{ cm}^{-3}$ ) layer, followed by a 2000 Å thick undoped barrier layer, a 3000 Å thick n-GaAs ( $N_d = 1.8 \times 10^{18} \text{ cm}^{-3}$ ) layer, and finally a 2000 Å thick heavily Si-doped n<sup>+</sup>-GaAs cap layer. The detailed structure near the barrier layer is also shown in Fig. 1. One is the bulk sample whose barrier layer is composed of undoped 2000 Å thick  $Al_{0.2}Ga_{0.8}As$  bulk material, and the other is an MQB sample of which barrier layer is composed of an undoped 2000 Å thick MQB. This MQB consists of 24 pairs of superlattice (34 Å GaAs / 34 Å  $Al_{0.2}Ga_{0.8}As$ ). Both sides of the superlattice are sandwiched with relatively thick (170 Å)  $Al_{0.2}Ga_{0.8}As$  layer to avoid the penetration of low energy electrons into the MQB region by resonant tunneling.

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The electron wave reflectivity of the MQB used in this study was calculated in the same manner as described in ref.1 and 2. In this calculation, we have used the 60 % rule<sup>9</sup>) for the conduction-band discontinuity  $\Delta E_c$  and its value is 149.6 meV. The virtually increased potential barrier height  $\Delta U_e$  enhanced by this MQB is calculated to be 88.5 meV.

In such a device, the current across the barrier layer under highly biased condition is mainly due to the tunneling current which transmits through the barrier layer as a result of the increase of transmission probability. Under almost zero biased condition, however, the transmission probability is almost zero, so the current is mainly due to the electrons of which energy is above  $\Delta E_c$ . Therefore, we can observe the increase of the potential barrier height due to the MQB by evaluating the I-V characteristic under almost zero biased condition. We have measured their I-V characteristics at liquid nitrogen temperature.

### 3. Results and Discussion

Figure 2 shows a typical I-V characteristic for two types of diodes measured at 77 K. The I-V curve of the MQB sample shows a clear rectification characteristic and has a higher turn-on voltage than that of the bulk barrier. This represents that electrons in the n-GaAs layer feel a high potential of the MQB barrier. To examine the  $\Delta U_e$  value under zero biased condition, we have measured the I-V characteristic in more detail. Figure 3 shows the experimental and theoretical I-V curves in a log scale. Two bold lines represent the experimental results of the bulk and MQB samples, respectively. Nine fine lines represent theoretical results by assuming the bulk barrier with various  $\Delta E_c$  value<sup>8</sup>). Each line corresponds to the  $\Delta E_c$  value from 149.6 meV to 229.6 meV with an increment of 10 meV from the upper side. The I-V curves strongly depend on  $\Delta E_c$  value and run parallel with each

other by changing the  $\Delta E_c$  value. They shift more than half order for only 10 meV increase of  $\Delta E_c$ .

The I-V curve of the bulk sample agrees very well with the theoretically calculated result using the  $\Delta E_c$  value as 149.6 meV. This supports the 60 % rule of conduction-band discontinuity  $\Delta E_c$ . The I-V curve of the MQB sample behaves very differently from that of bulk sample, and this indicates that electrons are well reflected by the MQB. Particularly, in the case of lower applied voltage, the difference from the bulk line is remarkable. We can estimate the effective potential barrier height  $\Delta U_e$  by the MQB under zero biased condition by comparing with theoretically calculated nine lines. At the vicinity of 0 Volt, it crosses the theoretical line of which barrier height is  $\Delta E_c + 80$  meV. This indicates that under zero biased condition electrons feel the barrier height of  $\Delta E_c + 80$  meV. Therefore, the  $\Delta U_e$  value is estimated to be equivalent to about 80 meV increase of  $\Delta E_c$ . This value is in good agreement with the theoretically expected  $\Delta U_e$  value of 88.5 meV.

Moreover, negative differential conductance can be seen in the MQB sample. We think that this could be due to electron wave resonance, but we have not confirmed it in detail yet. In any way, this phenomenon supports that the quantum effect contributes to the current-voltage characteristics.

### 4. Conclusion

We have shown the direct observation of the electron wave reflection and the superiority in the carrier confinement effect of the MQB over the bulk barrier in the n-GaAs/i-barrier/n-GaAs tunneling diode. Virtually increased potential barrier height by the MQB was measured to be 80 meV which is in good agreement with theoretical prediction. This first quantitative confirmation will encourage the development of new devices using the MQB

concept. Especially, in AlGaInP visible lasers, the MQB will contribute to its wavelength shortening.

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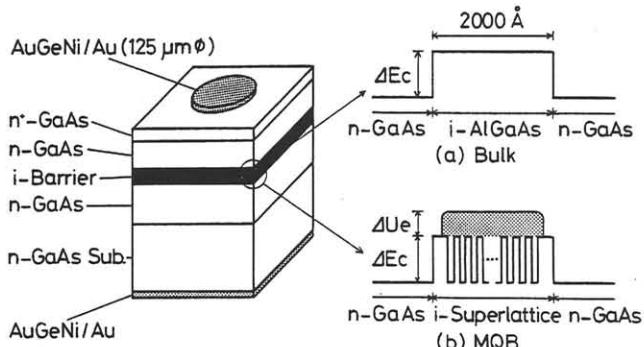


Fig. 1 Device structure of a n-GaAs/i-AlGaAs/n-GaAs tunneling diode. Detailed structure around the barrier layer is also shown.

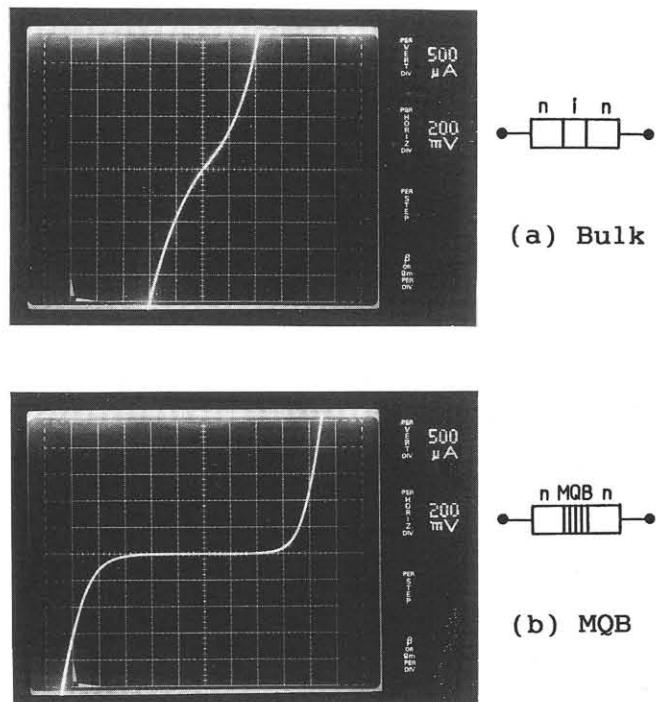


Fig. 2 Typical current-voltage characteristics of two types of diodes measured at 77 K.

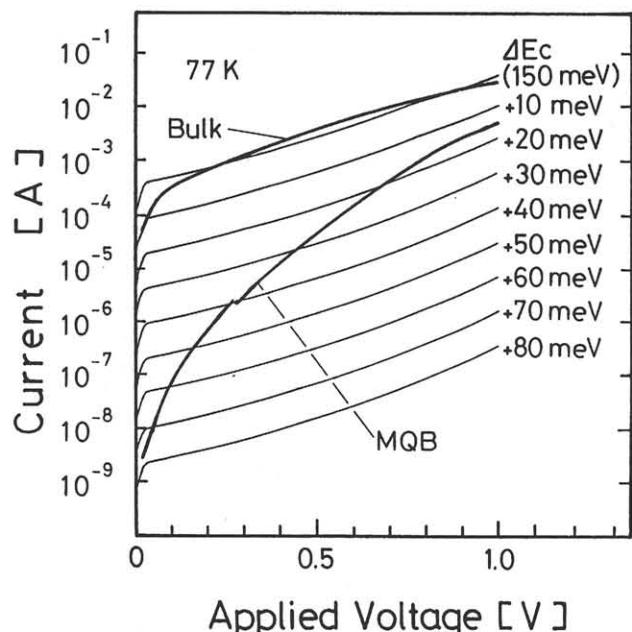


Fig. 3 Current-voltage characteristics of experimental and theoretically calculated results.