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Electroluminescence in Undoped GaAs/AlAs Superlattices due to Avalanche Breakdown

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1. Introduction

Avalanche breakdown has been used in photodetectors to achieve high-speed and high-sensitivity operation. The mechanism for the breakdown originates from the impact ionization resulting from an acceleration of carriers under a high electric field. However, electron transport in semiconductor superlattices (SLs) under avalanche breakdown has been a subject of controversy. [1] Thus, few investigations have been made on electron and hole recombination under avalanche breakdown in SLs.

In this report, we present the observation of electroluminescence (EL) in undoped GaAs/AlAs SLs due to the recombination of secondary electrons and holes by the impact ionization resulting from avalanche breakdown. From this observation, we expect novel devices such as high - speed light amplifiers to be developed.

2. Experimental

The sample studied is a GaAs/AlAs type- I SL embedded in a p-i-n diode structure grown on a (0,0,1)-oriented n^+- GaAs substrate by molecular beam epitaxy (MBE). The growth sequence of the sample is as follows: n^+- GaAs buffer layer, n-$Al_{0.5}Ga_{0.5}As$ cladding layer, nominally undoped 100 - period GaAs/AlAs (25/16 ML) SL layer sandwiched by 50 nm $Al_{0.5}Ga_{0.5}As$ undoped cladding layers, p- $Al_{0.5}Ga_{0.5}As$ cladding layer, and p^+- GaAs cap. The sample is structured into p - i - n diode mesas of 400 μ m squares. Alloyed electrodes are prepared to apply the electric field to the intrinsic region, and the ohmic contact is confirmed by examining the current- voltage (i - V) characteristics.

A low leak current of the device on the order of 10^{-10} A in the i - V characteristics excluded any contribution of defects concentrated in the barriers or quantum well (QW). The calculated Γ_1 energy was confirmed by photocurrent spectra and photoluminescence (PL) measurements. A cw HeNe laser beam is focused by a

10× objective lens on the p-cap side to generate carriers. The sample is cooled to 18K. The PL and EL from the sample in the cryostat is measured by a set of a monochromator and a high-sensitivity streak camera (Hamamatsu C4334). The i - V characteristics are measured with a semiconductor parameter analyzer (HP 4145B).

3. Results and Discussion

Figure 1 shows i - V characteristics for several laser intensities. The built-in voltage is about 1.5 V. We can clearly see that photocurrent as well as dark current rapidly increase with increasing the bias voltage beyond 42 V. According to our calculation, X_1 - Γ_2 resonance occurs at about 30 V, which is known to enhance carrier transport in SLs [2, 3]

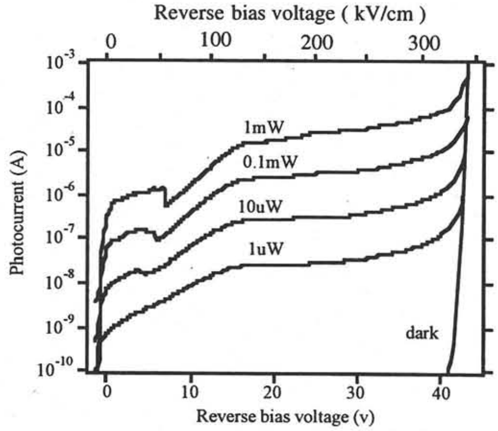

Figure 1: i - V curves at several levels of excitation laser power at 18K.

Figure 2 shows PL spectra as a function of the reverse bias voltage for a laser intensity of 1mW. A PL line exhibiting a red shift due to quantum confined Stark effect (QCSE) at around 765 nm is clearly observed. This PL line can be identified as Γ_1 - hh_1 PL. On the other hand, another PL line of a higher subband at 675 nm can be observed for applied electric fields of 190 and 240 kV/cm. This PL wavelength agrees well with the Γ_2 - hh_1 optical transition energy. Here, the forbidden transition between Γ_2 - hh_1 is allowed under a sufficiently strong electric field. Under such an electric field, a number of electrons are injected into Γ_2 due to the resonance of Γ_1 - Γ_2 or X_1 - Γ_2. As the electric field increases beyond 240 kV/cm, the Γ_2 - hh_1 PL intensity decreases. However, another broad PL spectra is detected at around 320 kV/cm, whose wavelength is shorter than that of the Γ_2 - hh_1 PL. Accordingly, this PL is thought to originate from the relaxation of the hot electrons that accompany the avalanche breakdown.

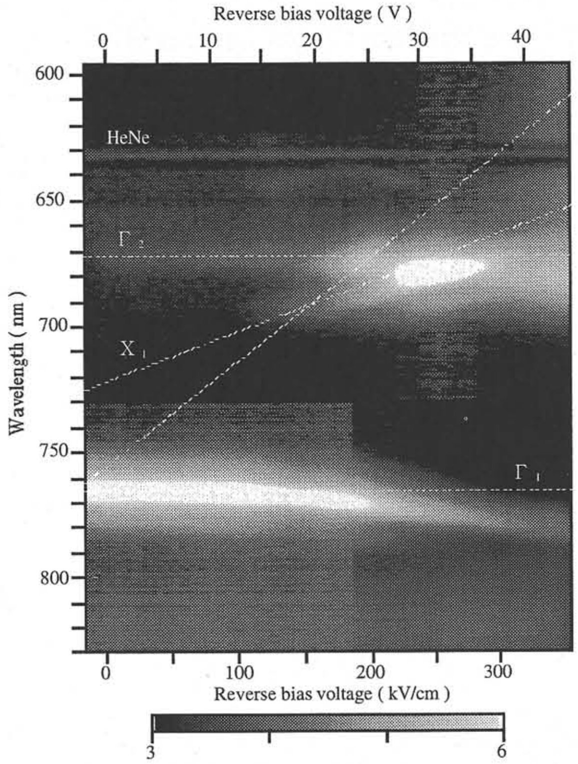

Figure 2: PL spectra as a function of the reverse bias voltage for a laser intensity of 1mW. The brightness is proportional to the logarithm of PL intensity. The intensity range to display the gray level is different in two areas: The top area from 600 - 730 nm shows an approximately 6×10^{-4} intensity range compared to the area of 730 - 830 nm for displaying weak PL. The white dotted lines show the calculated energies which do not take into account the exciton binding energy.

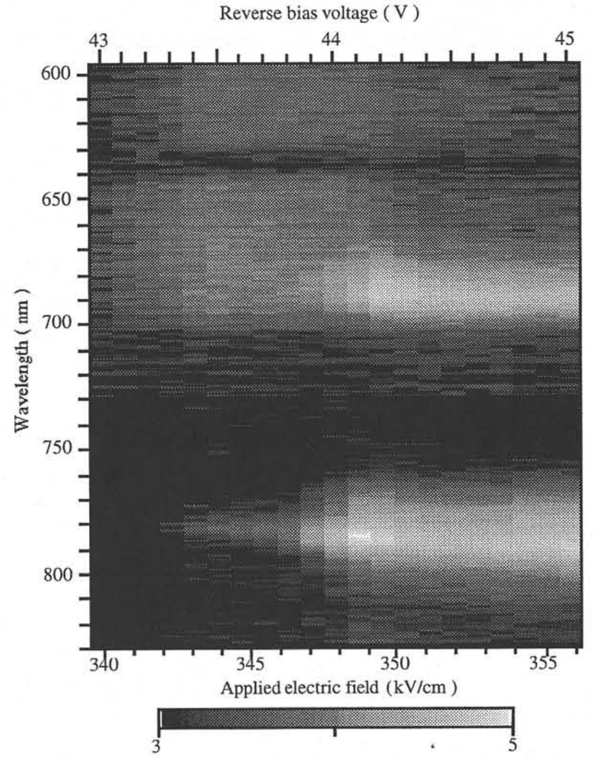

Figure 3: EL spectra as a function of the reverse bias voltage. The brightness is proportional to the logarithm of EL intensity. The intensity range to display the gray level is different in two areas: The top area from 600 - 730 nm shows an approximately 10^{-1} intensity range compared to the area of 730 - 830 nm for displaying a weak EL.

Figure 3 shows measured EL spectra as a function of the reverse bias voltage at around the breakdown voltage. In the EL measurement, the sample is not irradiated by a cw laser anymore. The EL starts to be observed at around 341 kV/cm. On the contrary, PL due to hot electrons shown in Figure 2 starts to be observed at 320 kV/cm. Thus, the initial electric field for EL is higher than that for PL due to hot electrons. This is probably because the carrier density in PL measurements is larger due to the use of laser excitation. Comparing the current densities at the PL beginning electric field 320 kV/cm (see Figure 1), the dark current is clearly much smaller than other photocurrent values, indicating larger carrier densities in PL measurements. Two peaks can be observed in the EL measurement at around 350 kV/cm. Such luminescence is unquestionably different from the broad luminescence due to hot electrons. The energies 780 nm and 680 nm corresponding to the EL wavelength at 350 kv/cm agree well with Γ_1 - hh_1 and Γ_2 - hh_1, respectively. The Γ_2 - hh_1 PL intensity is comparatively strong. This enhance of the Γ_2 - hh_1 PL is caused by an increase of an electron density in the Γ_2 state. A large amount of electrons are injected to the Γ_2 state by X_1 - Γ_2 transfer. In addition, another large amount of electrons may relax into the Γ_2 state, because of the hot PL spectra indicate that many electrons have higher energies than the Γ_2 state.

4. Conclusion

We have observed EL in an undoped GaAs/AlAs SL due to avalanche breakdown. The Γ_2 - hh_1 radiative recombination clearly demonstrates that a large amount of electrons are injected to Γ_2 state.

Acknowledgments

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