Temperature dependence of photoluminescence of an *n-i-p-i* GaAs superlattice

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Both the photoluminescence peaks corresponding to the vertical transitions and the nonvertical transitions in an *n-i-p-i* GaAs superlattice are clearly observed. The redshifts of the two peaks with increasing temperature are discussed in terms of the temperature-dependent carrier separation effect.

Since the concept of doping superlattice was proposed by Esak and Tsu,[1] the electronic properties of it were intensively investigated both theoretically and experimentally.[2–11] Doping superlattices are structures which contain alternatively *n*-type and *p*-type doped regions of one semiconductor material and have a number of unique properties, such as tunable electronic structures, indirect band gap in real space, and large recombination lifetimes. These properties are originated from the spatial separation of electrons and holes due to the periodic impurity space charge potential and can be utilized in semiconductor devices such as light-intensity modulators. Great efforts have been put on the tunable and indirect band-gap transitions of *n-i-p-i* superlattices. The possible vertical optical transitions in *n-i-p-i* superlattices are also investigated by temperature-dependent photoluminescence (PL) experiments.[7–9] However, these reports only discussed the overall PL intensity dependence on temperature and the critical temperature point at which vertical transitions will prevail in intensity according to the sample parameters. To our surprise, no discussions on the PL peak energy dependence on temperature were performed in the large body of previous research in this field. In this paper, we investigate the temperature-dependent PL properties of an *n-i-p-i* GaAs superlattice. Both PL peaks from indirect transitions and direct transitions are clearly observed, the redshifts of the two peaks with increasing temperature are discussed in terms of the competition of the direct and indirect transitions in the *n-i-p-i* GaAs superlattice.

The sample was grown by molecular-beam epitaxy (MBE) on a (001) N^+ GaAs substrate, after deposition of 1 μm semi-insulating GaAs buffer layer, ten periods of *n* GaAs (40 nm)/*p* GaAs (40 nm) was grown. *n* GaAs was Si doped and *p* GaAs was Be doped, both *n* and *p* doping concentration is $1\times10^{18}\,\mathrm{cm}^{-3}$. The overall structures were grown at 520 °C. The PL was performed in a Fourier transform spectrometer equipped with an InGaAs detector. The spectra were obtained under excitation with the 514.5-nm line of an argon-ion laser.

Figure 1 schematically shows the band diagram of the *n-i-p-i* GaAs superlattice along the growth direction. At low temperatures and low excitation power densities, only indirect transitions (which is marked by arrow b in Fig. 1) between spatially separated electrons and holes are expected. At higher temperatures or higher excitation power densities, due to the band filling effect and the carrier thermal distribution, vertical transitions in the *n*-doped layers and the *p*-doped layers are physically possible. Arrow a indicates the vertical transitions between electrons in conduction subbands and holes in quasicontinuum valence band in the *n* layers. Arrow c represents the vertical transitions between electrons in the continuum conduction band and the holes in the acceptor impurity bands in the *p* layers. From Fig. 1, It is seen that the ground transition energy in the *n* layers is larger than GaAs band gap, and the ground transition energy in the *p* layers is smaller than GaAs band gap. Due to the larger effective mass of heavy holes and the resulting larger acceptor binding energy, holes will populate an acceptor band rather than valence subbands.[6] And the number of subbands for holes, the two-dimensional state density of holes are much larger than that of electrons. Therefore it is difficult to populate holes in high index valence subbands or the con-

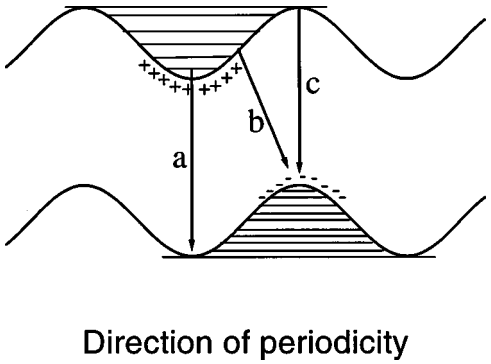

FIG. 1. Band diagram of the *n-i-p-i* GaAs superlattice along the growth direction.

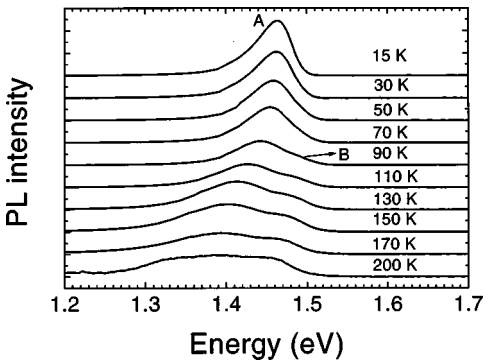

FIG. 2. The PL spectra of the *n-i-p-i* GaAs superlattice at various temperatures under an excitation power density of 10 W/cm^2. The temperatures are 15, 30, 50, 70, 90, 110, 130, 150, 170, 200 K. For clear comparison, all the spectra are multiplied and are shifted vertically.

tinuum valence band both by photoexcitation and thermal excitation when compared with that for electrons. Thus it can be expected that the PL from vertical transitions in the *p* layers will be much stronger than that from the *n* layers. This may be the reason that a peak corresponding to vertical transitions in the *p* layers is observed in our experiment, whereas no peak corresponding to vertical transitions in the *n* layers is observed.

Figure 2 shows the PL spectra of the *n-i-p-i* GaAs superlattice in the temperature range 15–200 K under an excitation power density of 10 W/cm^2. At low temperatures, one peak is observed which is marked by A in Fig. 2. When the temperature is increased to 90 K, a new peak appears (marked by B in Fig. 2). When further increasing temperature, peak B becomes more and more obvious in the whole PL spectrum. Excitation intensity dependent PL experiments at various temperatures show that peak A blue shifts rapidly with increasing excitation intensity, whereas the position of peak B is basically power independent. Figure 3 shows the power-dependent PL spectra at 170 K, it is clearly seen that with increasing excitation power density, the intensity of peak B increases faster than that of peak A.

We will now discuss peak A and B. Due to the large blue shift with increasing the excitation intensity, it is clear that peak A results from the nonvertical transitions. From the energy of peak B (1.484 eV at 90 K, GaAs band gap is 1.504

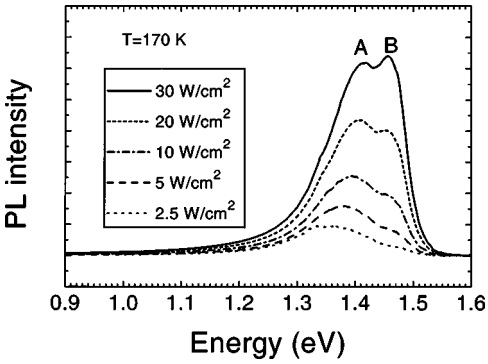

FIG. 3. The PL spectra of the *n-i-p-i* GaAs superlattice under various excitation power densities at 170 K. The excitation power densities are 2.5, 5, 10, 20, 30 W/cm^2.

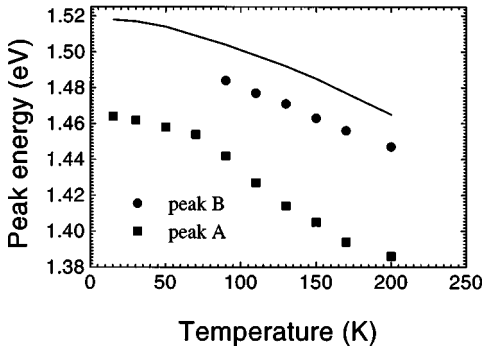

FIG. 4. The energy of peak A and peak B as a function of temperature under an excitation intensity of 10 W/cm^2. The continuous line is for GaAs band gap calculated according to the Varshni law.

eV at this temperature), it should originate from the vertical transitions in the *p* layers. The position energy of peak B is also compatible with $\hbar w = E_g - E_d - E_a + e^2/4\pi\varepsilon\varepsilon_0 r$, the energy for DA pair luminescence, but for DA transition, when increasing temperature, due to the rapid ionization of shallow impurity Si (ionization energy is only about 5 meV), the PL should decrease very rapidly. In our experiment, the intensity of peak B decreases very slowly and it tends to dominate the whole PL at higher and higher temperatures. Thus we think peak B should be related to the vertical transitions in the *p* layers. No peak corresponding to vertical transitions in the *n* layers is observed, possible reasons have been proposed above.

Figure 4 shows the position dependence of peak A and peak B on the temperature under an excitation intensity 10 W/cm^2, the continuous line is for GaAs band gap calculated according the Varshni law using the parameters of GaAs.[12] In the temperature range of 15–70 K, the redshift of peak A is similar with the shrinkage of GaAs band gap. When the temperature exceeds 70 K, the red shift of peak A becomes faster than the shrinkage of GaAs band gap, whereas the redshift of peak B is always similar with the shrinkage of GaAs band gap in the temperature range 90–200 K. The energy difference of peak B and GaAs band gap is about 20 meV. This is consistent with the corresponding energy of vertical transitions in *p* layers which is shown in Fig. 1 (the energy difference should be the ionization energy of Be which is about 28 meV, in case of heavy doping, this energy will decrease). With increasing temperature, for peak A, except that it will redshift together with the GaAs band gap, it will also be affected by the modulation effects of separated photogenerated carriers to the doping potential. The more the spatially separated electrons and holes, the more the doping potential is decreased or flattened, and the higher the position energy of peak A. Between 15–70 K, the indirect band-gap transition is completely dominant, the number of spatially separated electrons and holes generated by a 10-W/cm^2 excitation intensity are almost constant in this temperature range, thus the doping potential is almost constant. So the position of peak A has the similar redshift with the GaAs band gap. When the temperature is higher than 70 K, the vertical transitions begin to become important in the PL process, some electrons and holes will recombine in vertical transitions and will not spatially separated. With further in-

creasing the temperature, more and more electrons and holes will recombine in vertical transitions and the spatially separated electrons and holes become less, thus the modulation effect of photogenerated electrons and holes to the doping potential will become smaller, the doping potential well will become deeper. Therefore the redshift of peak A becomes faster than the shrinkage of GaAs band gap. Meantime, due to thermal distribution effect, it can be expected that the vertical transition will become more and more important in the PL process with increasing temperature or with increasing the excitation intensity at relatively high temperatures, this can be clearly seen in Figs. 2 and 3.

In summary, we have investigated the temperature-dependent PL properties of an *n-i-p-i* GaAs superlattice. At low temperatures, the PL peak from the indirect tunable band gap of the *n-i-p-i* GaAs superlattice is observed. With increasing temperature, a peak appears at the high-energy side in the photoluminescence spectrum, and it tends to dominate the whole photoluminescence at higher temperatures or higher excitation power densities. We believe the peak originates from the vertical transitions in the *p*-doped layers of the *n-i-p-i* GaAs superlattice. The redshifts of the two peaks with increasing the temperature are also discussed in terms of the competition of the nonvertical transitions and vertical transitions.

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