Electroluminescence from a forward-biased Schottky barrier diode on modulation Si δ-doped GaAs/InGaAs/AlGaAs heterostructure

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(Received 22 January 2001; accepted for publication 2 May 2001)

Electroluminescence (EL) from a forward-biased Schottky barrier diode on modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs heterostructure with high mobility electron gas is investigated in this work. It has been found that the EL from the InGaAs quantum well can be observed at temperatures up to 90 K. The EL line shape depends on the current density, which reflects the filling of the InGaAs channel with electrons. The total integrated EL intensity depends linearly on the current density. We propose that hole diffusion from an inversion layer at the Schottky barrier is responsible for the observed optical recombination with electrons in the InGaAs quantum well. [DOI: 10.1063/1.1380397]

Schottky barriers (SBs) have been studied from early years of semiconductor physics.[1] Such metal–semiconductor contacts supply usually majority carriers to semiconductor material. However in some situations minority carrier injection must be taken into account as well. Minority carrier injection leads to several potential applications, e.g., in BARRITT diodes.[2] Light-induced electron injection from the SB on p-doped GaAs/InGaAs quantum well (QW) has recently been used in near-infrared to visible light up-conversion devices.[3] Quite recently a structure with ferromagnetic SB has also been proposed as a possible candidate for ''spintronic'' device, in which electron spin, rather than electron charge can be controlled.[4] Minority carrier injection in a SB diode can give rise to generation of light. Although that effect has been observed for several years[5,6] no systematic study of the electroluminescence (EL) from SB diodes on low dimensional structures has been published. In our opinion electrically driven light emission from such structures, besides the general interest, may be of some potential applications. In this letter we show that light can be emitted from the forward-biased SB diode on modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs heterostructure at low temperature.

A structure used for this study (see Fig. 1) was grown by a low pressure metalorganic chemical vapor phase epitaxy at the Australian National University. It consisted nominally of 600 nm GaAs buffer layer, 90 nm of (5 nm $Al_{0.2}Ga_{0.8}As$/5 nm GaAs) short period superlattice, 310 nm $Al_{0.2}Ga_{0.8}As$ back barrier, pseudomorphic 10 nm $In_{0.2}Ga_{0.8}As$ QW, and 205 nm GaAs top barrier. The Si δ-doping layer ($2.3\times10^{12}\,cm^{-2}$) was grown 10 nm from the QW in the back barrier. Similar δ-doping was applied 5 nm below the structure surface in order to saturate surface states. Magnetotransport measurements at low temperature confirmed the formation of high mobility ($\mu=46\,000\,cm^2/V\,s$) quasi two-dimensional electron gas ($n=1.08\times10^{12}\,cm^{-2}$ in the dark) in the QW.[7] Ohmic contacts were made by Au/Ge alloying and a semitransparent Au Schottky gate was formed by thermal evaporation on the top of the structure. The EL and photoluminescence (PL) measurements were performed in an optical cryostat and collected using a charge coupled device camera or Ge nitrogen cooled p-i-n diode. The PL spectra were excited using He–Ne ($\lambda=632.8$ nm) or semiconductor ($\lambda=780$ nm) laser.

PL and EL spectra measured at $T=10$ K are presented in Fig. 2. Three groups of distinctive features can be seen in the PL spectrum. These are due to: (1) optical recombination within the InGaAs QW, (2) conduction band-to-neutral carbon acceptor transition ($E=1.49$ eV) and bound exciton ($E=1.515$ eV) from the top GaAs barrier, and (3) interminibands transitions in the AlGaAs/GaAs superlattice. Two peaks observed from the QW are due to $1e-1hh$ ($E=1.339$ eV) and $2e-1hh$ ($E=1.388$ eV) transitions. The latter transition, forbidden by parity rules in the symmetric QW becomes allowed due to deformation of QW potential resulting from the electric charge in the doping layer.[8] On the other hand the EL spectrum recorded at current density $j=16\,mA/cm^2$ reveals only transitions from the QW. At larger current density (not shown in Fig. 2) a weak feature at $E=1.49$ eV from the top GaAs layer can also be observed. The QWs EL line shape depends on the current density as well. Both peaks shift toward higher energies with increasing current. The higher electron density in the QW the more effec-

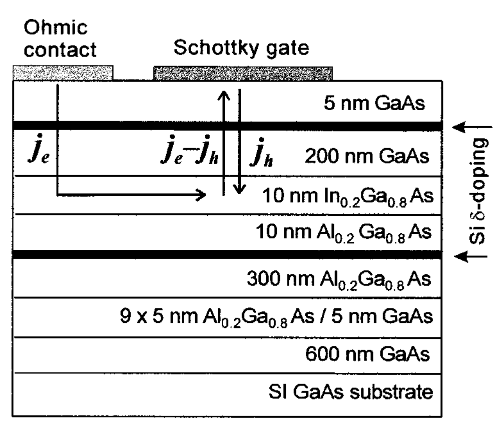

FIG. 1. A sample structure with schematically shown majority-carrier (j_e) and minority-carrier currents (j_h).

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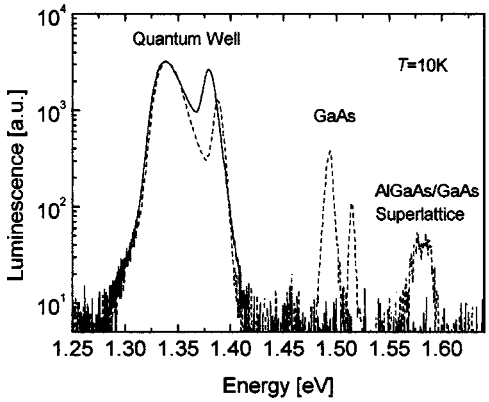

FIG. 2. Electroluminescence at $j=16\ \mathrm{mA/cm^2}$ (solid line) and photoluminescence (dashed line) from the modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs heterostructure at $T=10$ K.

tive screening of electric charge in the doping layer. This changes the QW potential to more symmetric and then leads to a modification of the transitions energies. An increase of the EL intensity at the high energy side of the spectrum with increasing current density is also observed, which probably reflects the QW filling with electrons.

The EL from the GaAs/InGaAs/AlGaAs high electron mobility transistors has been studied extensively in recent years.[9] Hot carriers and impact ionization are believed to be responsible for broadband light emission observed in those devices. On the contrary diffusion of holes from an inversion layer at the SB seems to be responsible for the phenomena observed in our experiment. Injection of minority carriers into the semiconductor, although usually very small, is not always completely negligible,[10] especially if the SB height is great enough. An inversion p-type layer forms at the metal–semiconductor interface in such a case, which supplies minority carriers into the structure. Hole diffusion current j_h flows from that layer towards the QW. Once past the zero-field point the current j_h changes its character from diffusive to drift[11] and finally holes decay radiatively in the QW. Due to a very high electron density in the QW most holes are likely to recombine, and purely electron current j_e flows in the QW towards an ohmic contact. The EL spectrum reflects the electron density in the structure. Predominant are peaks due to transitions within the QW with large electron density and holes supplied by the j_h current. The peak at $E=1.49$ eV from the top GaAs layer can be observed at large current densities when the hole current j_h and electron current j_e densities are high enough to account for optical recombination in that region. A hole-injection ratio $\gamma_n=j_h/j_e$[12] does not depend on the total current density j_e in a low-injection mode. This leads to a linear dependence of the total EL intensity on the current density. Such a dependence observed in our experiment (see Fig. 3) confirms proposed attribution of the EL to optical recombination of electrons in the QW with holes supplied by the minority-carrier current j_h.

The γ_n ratio depends also on the hole diffusion constant D_p, which leads through the Einstein relation: $kT\mu_h=qD_h$ to the EL dependence on the hole mobility μ_h in the top GaAs layer. This probably explains the maximum in the temperature dependence of the total integrated EL intensity observed around $T=70$ K (see Fig. 4), which may be due to a peak in the hole mobility μ_h.[13] More detailed analysis of the recombination processes leading to the EL in the investigated device is necessary to confirm this suggestion. Such an analysis should also provide information on the minority-carrier mobility perpendicularly to a structure plane.

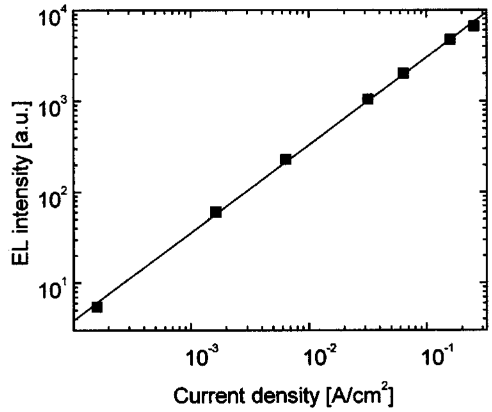

FIG. 3. Linear dependence of the integrated electroluminescence intensity as a function of current density at $T=4.2$ K.

Along with investigation of basic properties of low dimensional structures, some possible applications of the observed effect can be proposed as well. A thermal quenching of the EL may be very likely overcome using a deeper confining potential (e.g., of quantum dots) in the active region. The EL from ferromagnetic–metal SB diodes can also be interesting from "spintronic" point of view. Although direct spin injection from the metal to semiconductor is known to be ineffective,[14] a possible spin polarization of holes in the inversion layer at the ferromagnetic SB due to a proximity effect can be expected. The structures such as discussed here seem to be ideal to investigate this concept in detail.

In conclusion a light emission from a forward-biased SB diode on the modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs heterostructure has been studied. It has been found that the EL from InGaAs QW can be observed at low temperature. Linear dependence of the total integrated EL intensity on the current density has been found. A hole diffusion from an inversion layer at the SB was proposed as a source of holes for the observed optical recombination. A temperature dependence of the total EL intensity with a

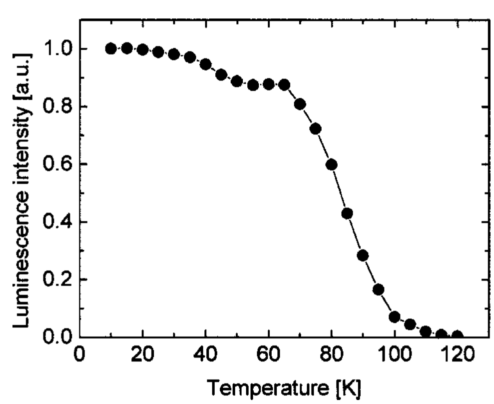

FIG. 4. Temperature dependence of the total integrated electroluminescence from the Schottky barrier diode on the modulation Si δ-doped pseudomorphic GaAs/InGaAs/AlGaAs heterostructure at low temperature. Current density was equal to $j=16\ \mathrm{mA/cm^2}$.

maximum around $T = 70$ K has been proposed to be due to a temperature dependence of the hole mobility in the GaAs front barrier. Possible applications of the observed effect have been suggested.

This work was supported in part by Polish Scientific Committee Grant No. 2 P03B 043 18. Assistance from Dr. S. Lavorik is gratefully acknowledged. Help from Professor C. Jagadish and Dr. G. Li from The Australian National University with the structure growth is gratefully acknowledged.

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