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Selective electroluminescence from a single stack of sidewall quantum wires on patterned GaAs (311)A substrates

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A *p-i-n* light-emitting diode (LED) with a single stack of sidewall quantum wires in the center of the intrinsic region has been fabricated by molecular-beam epitaxy on patterned GaAs (311)A substrates with all-Si *n*- and *p*-type doping. For small injection currents, the electroluminescence (EL) measured at low temperatures solely originates from the quantum wires without emission from the surrounding quantum wells within the patterned LED of 220 μm diameter. The selectivity of the EL emission is gradually reduced with increasing temperature, but the emission intensity per unit area in the wire regions is still two orders of magnitude larger than that in the well regions at room temperature. A model based on the lateral diffusion of injected electrons and holes is proposed to explain the selective carrier injection into the quantum wires. © *1999 American Institute of Physics.* [S0003-6951(99)01439-4]

The operation of light-emitting devices based on lateral nanostructures, i.e., quantum wires and quantum dots, crucially depends on the underlying mechanism for carrier injection and capture. These mechanisms may be remarkably different from beam excitation techniques such as photoluminescence (PL) or cathodoluminescence (CL), usually employed to characterize optical properties.[1] In this letter, we demonstrate a *p-i-n* light-emitting diode (LED) with a single stack of GaAs/(AlGa)As sidewall quantum wires in the center of the intrinsic region exhibiting highly selective electroluminescence (EL) between 10 K and room temperature. The quantum wires are grown by molecular-beam epitaxy (MBE) on patterned GaAs (311)A substrates with a well defined position on the wafer surface.[2] Their formation relies on a growth mechanism at [01-1] oriented mesa stripes producing a fast growing sidewall with a very smooth, unfaceted, convex surface profile. For mesa heights in the quantum size regime (10–20 nm), the quasiplanar sidewall quantum wires exhibit high PL efficiency and clear one-dimensional quantization in low-temperature PL excitation spectroscopy.[3] They can be stacked in dense arrays[4] and transformed to very uniform linear arrays of quantum dots by atomic-hydrogen-induced self-faceting across the fast growing sidewall.[5]

At low temperatures and small injection currents, the EL of our quantum-wire LED solely originates from the single stack of quantum wires within the 220-μm-diam mesa patterned device without detectable emission from the surrounding quantum wells. Although the EL from the quantum wells increases relative to that from the quantum wires with increasing temperature, the EL emission density, i.e., intensity per unit area in the wire regions, is still two orders of magnitude larger than that in the well regions even at room temperature. The spatially well defined emission pattern from the quantum wires is directly observed through an optical microscope as a bright line within the otherwise dark mesa. A model based on the lateral diffusion of electrons and holes is proposed to account for the highly selective EL due to self-enhanced carrier injection into the quantum wires.

The *p*-type GaAs (311)A substrates were patterned with mesa stripes of 75 μm width and 17 nm depth along the [01-1] direction by standard photolithography and wet chemical etching.[2] After cleaning with concentrated sulphuric acid and rinsing in de-ionized water, the sample was transferred into the MBE growth chamber where the native oxide was desorbed at 580 °C. The Si-doped 50-nm-thick p^+- (1×10^{18} cm^{-3}) GaAs buffer layer and 100 nm p- (0.6×10^{18} cm^{-3}) Al$_{0.3}$Ga$_{0.7}$As layer were grown at 610 °C with an As/Ga flux ratio of 5 so that Si is incorporated as an acceptor. A 400-nm-thick intrinsic Al$_{0.3}$Ga$_{0.7}$As layer was grown under the same conditions with a stack of two 3-nm-thick GaAs quantum-well layers separated by a 2 nm Al$_{0.3}$Ga$_{0.7}$As barrier layer inserted in its center. After growth of the intrinsic layer, the substrate was cooled down to 490 °C and, simultaneously, the As/Ga flux ratio was increased to 20 in order to obtain *n*-type doping by Si[6] for the following 100 nm n- (0.6×10^{18} cm^{-3}) Al$_{0.3}$Ga$_{0.7}$As layer capped by a 40 nm n^+- (1×10^{18} cm^{-3}) GaAs contact layer. The as-grown structures were processed into circular mesas of 220 μm diameter etched down to the p-Al$_{0.3}$Ga$_{0.7}$As layer with ohmic Au/Be ring contacts on the mesa top and ohmic Au/Ge back contact layer. The mesas were positioned in such a way that only one stack of wires is located inside the ring contact. The use of a single stack of quantum wires enhances the overall efficiency of the LED. It is, however, not relevant for the selective carrier injection discussed here. The samples were characterized by micro-PL, CL, as well as electron beam induced current (EBIC) measurements before examining their EL properties.

Figure 1 shows the EL spectra for increasing forward bias detected at 10 K through a confocal imaging system with the diameter of the optical probe area of 10 μm. Starting from the onset of the EL at about 1.8 V, strong emission is only observed from the quantum wires up to a forward

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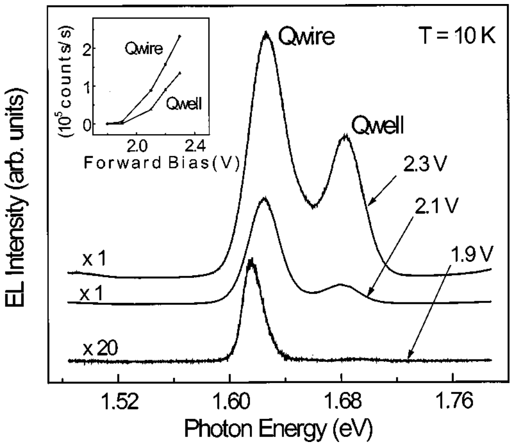

FIG. 1. EL spectra of the quantum-wire LED detected at 10 K for increasing forward bias. Inset: peak intensity of the quantum wire and quantum well EL as a function of forward bias.

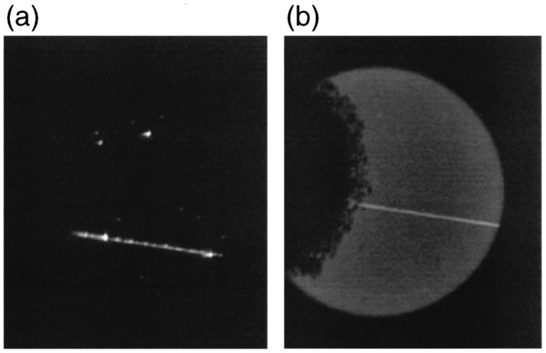

FIG. 3. Images of the EL through an optical microscope (a) at 10 K and (b) at room temperature. The inner diameter of the ring contact is 120 μm.

bias of 1.9 V (0.7 mA). With increasing bias from 2.1 V (1.3 mA) to 2.3 V (3.2 mA), a weak emission from the quantum wells appears, which grows in intensity more slowly compared to that of the quantum wires. The EL peak intensities of the quantum wires and quantum wells increase almost linearly with current in the measured regime. The absolute current values, however, may vary by several mA from measurement to measurement and after subsequent sample cooling most probably due to persistent photoconductivity effects in the (AlGa)As layers at low temperatures. The dependence of the EL peak intensities of the quantum wires and quantum wells on forward bias (see inset of Fig. 1) clearly indicates selective carrier injection into the quantum wires, which is most effective at the onset of the EL signal. The blueshift and linewidth broadening of the quantum wire and quantum well EL lines for increasing forward bias are attributed to band filling effects.

Selective carrier injection into the quantum wires is observed up to room temperature. Figure 2 shows the EL spectra as a function of the temperature keeping the injection current fixed at about 5 mA together with the current–voltage characteristic at room temperature in the inset. With increasing temperature, the EL efficiency is reduced by nonradiative recombination channels as its selectivity. This is attributed to carrier heating increasing the carrier injection into the quantum wells relative to that into the quantum wires. However, taking into account the area ratio of the quantum well to quantum wire (diameter of the optical probe area divided by the effective quantum-wire width of 40–50 nm)[2] and assuming a comparable radiative efficiency of the quantum wells and quantum wires (indicated by the similar intensity ratio of the quantum well to quantum-wire emission at 10 K and room temperature in μ-PL)[2], the EL intensity per unit area and electron-hole pair density for the quantum-wire position at room temperature are still about two orders of magnitude larger than that of the quantum wells.

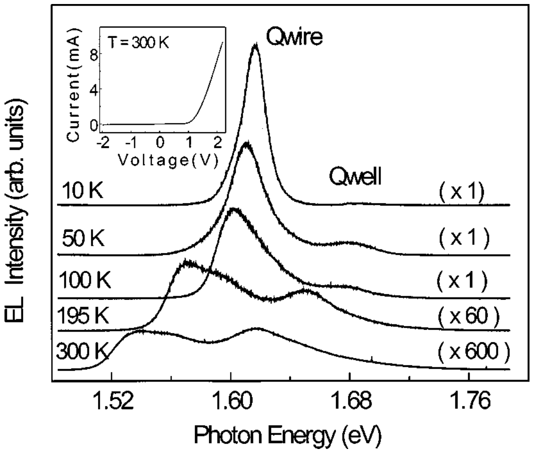

FIG. 2. EL spectra of the quantum-wire LED for about 5 mA forward current between 10 K and room temperature. Inset: current–voltage characteristic at room temperature.

As a consequence of the high emission density, the EL of the quantum wires is directly visible through an optical microscope as a bright line inside the ring contact [see the images in Figs. 3(a) and 3(b) taken at 10 K and room temperature corresponding to the respective spectra in Fig. 2]. At low temperatures [Fig. 3(a)], the bright quantum-wire EL is seen with several bright spots along its line, which appear also in the quantum well regions. These bright spots are attributed to several cluster-like defects in the quantum wires and quantum wells involving regions of lower band gap energy compared to that of the surrounding wire or well (the EL spectra taken from such clusters are broadened). Thus, similar selective carrier injection is assumed for these clusters. The corresponding band gap reduction deduced from the (low energy) line broadening of several meV is, however, much smaller than that of the quantum wires relative to the quantum wells of 70 meV. Therefore, the enhanced EL emission of these clusters vanishes at about 50 K due to the thermally activated escape of injected carriers, while that of the quantum wires persists up to room temperature. Consequently, the spatial homogeneity of the EL emission of the quantum wires at room temperature in Fig. 3(b) becomes much more uniform compared to that at low temperatures.

Before presenting our model to explain the strong EL selectivity in the present quantum wire LED, several alternative mechanisms have to be discussed. First, enhanced carrier capture in the quantum wires due to larger layer thicknesses. However, such an enhanced carrier capture would equally apply to μ-PL and CL measurements, where such strong enhancement of the quantum-wire emission is not observed. The μ-PL and CL measurements of the present LED and of undoped reference structures always reveal strong emission from the quantum well for comparable electron-hole pair generation density with similar radiative efficiency.[2] Second,

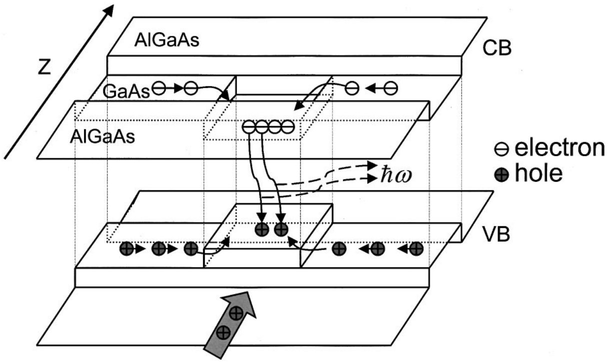

FIG. 4. Schematic illustration of the lateral diffusion of electrons and holes in the quantum well leading to selective carrier injection into the quantum wire. *Z* is the growth direction, the horizontal direction is across the wire region and the vertical one is energy.

reduced Al composition of the (AlGa)As barriers in the quantum wire regions providing injection channels of lower band gap energy. In fact, this injection mechanism has been discussed for metalorganic vapor phase epitaxy (MOVPE)-grown *V*-groove quantum wires due to the presence of the vertical quantum well in the (AlGa)As barriers.[7] The small 500 nm periodicity of the *V* grooves in Ref. 7, however, has been shown to result in almost complete suppression of the quantum well PL for our sidewall quantum wires due to efficient diffusion of free carriers into the wires (the diffusion length is in the μm range)[8] without the necessity of selective injection. Moreover, spatially resolved CL spectroscopy of the (AlGa)As barriers shows a negligible variation of the band gap energy, i.e., Al composition across our MBE-grown quasiplanar sidewall quantum wires. Third, nonuniform doping EBIC measurements, which are very sensitive to lateral potential modulations due to nonuniform doping (or Al composition) as well as carrier capture in the intrinsic region and neighboring doped layers,[9] reveal a contrast variation in the quantum-wire region of at most several percent. Finally, the vertical asymmetry of *V*-groove structures (the quantum wires are closer to the bottom contact than the quantum wells) has been considered in 4 μm pitch *V*-groove quantum wires showing a much smaller degree of EL selectivity.[10] However, our sidewall quantum wires are quasiplanar in geometry (for *T*-shaped quantum wires, no explanation has been given for the selective carrier injection at low temperatures in Ref. 11). From the above discussion, we exclude structural nonuniformities or carrier capture mechanisms to account for the observed EL selectivity in our quantum-wire LED and propose the following model.

Starting from a homogeneous injection of electrons and holes from the *n*- and *p*-type regions into the quantum wells and quantum wires, the carriers in the quantum wells diffuse laterally as free electrons and holes or excitons into the wires for distances within their diffusion length. From the fraction of electrons and holes diffusing separately, more electrons are trapped in the wires due to their larger migration length. Therefore, the wires become negatively charged so that they effectively attract holes and, most importantly, reduce their injection barrier into the wire region (see schematic illustration in Fig. 4). The same mechanism explains the bright EL at low temperatures from any cluster-like defect having a locally reduced band gap energy. Hence, unlike the beam excitation (PL and CL), the lateral diffusion of electrons and holes in EL affects the injection mechanism itself by increasing the current in the wire region. In addition, the fraction of electrons and holes diffusing separately may be enhanced in EL due to their separate injection, while for optical and beam excitation the generation of electrons and holes is correlated in space and time enhancing the probability for exciton formation. The result is selective carrier injection into the quantum wires with a steeper increase of the quantum wire EL compared to that of the quantum wells as a function of forward bias.

In conclusion, we have fabricated *p-i-n* light-emitting diodes employing a single stack of sidewall quantum wires on patterned GaAs (311)A substrates by MBE using all Si doping for the *n*- and *p*-type regions. The EL spectra show strong selectivity of the quantum-wire emission with a steeper increase in intensity compared to that of the surrounding quantum wells for increasing forward bias. The EL from the quantum wires is directly observed through an optical microscope as a bright line within the otherwise rather dark 220-μm-diam device. Up to room temperature, the emission density in the wire region is locally enhanced by up to two orders of magnitude compared to that from the quantum wells. To account for the highly selective EL, a model is proposed, which is based on the lateral diffusion of electrons and holes resulting in self-enhanced carrier injection into the quantum wires. Our results provide insight into the operation of light-emitting devices based on lateral nanostructures, which may be advantageous for optical fiber applications utilizing a locally enhanced emission density from single quantum wires and quantum dots.

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[1] *Optics of Semiconductor Nanostructures*, edited by F. Henneberger, S. Schmitt-Rink, and E. O. Göbel (Akademie, Berlin, 1993).
[2] R. Nötzel, M. Ramsteiner, J. Menniger, A. Trampert, H. P. Schönherr, L. Däweritz, and K. H. Ploog, Jpn. J. Appl. Phys., Part 2 **35**, L297 (1996).
[3] A. Richter, G. Behme, M. Süptitz, Ch. Lienau, T. Elsaesser, M. Ramsteiner, R. Nötzel, and K. H. Ploog, Phys. Rev. Lett. **79**, 2145 (1997).
[4] R. Nötzel, M. Ramsteiner, J. Menniger, A. Trampert, H. P. Schönherr, L. Daweritz, and K. H. Ploog, J. Appl. Phys. **80**, 4108 (1996).
[5] R. Nötzel, Z. C. Niu, M. Ramsteiner, H. P. Schönherr, A. Trampert, L. Däweritz, and K. H. Ploog, Nature (London) **392**, 56 (1998).
[6] N. Sakamoto, K. Hirakawa, and T. Ikoma, Appl. Phys. Lett. **67**, 1444 (1995).
[7] H. Weman, E. Martinet, A. Rudra, and E. Kapon, Appl. Phys. Lett. **73**, 2959 (1998).
[8] R. Nötzel, U. Jahn, Z. C. Niu, A. Trampert, J. Fricke, H. P. Schönherr, T. Kurth, D. Heitmann, L. Däweritz, and K. H. Ploog, Appl. Phys. Lett. **72**, 2002 (1998).
[9] H. T. Lin, D. H. Rich, O. Sjölund, M. Ghisoni, and A. Larsson, Appl. Phys. Lett. **69**, 1602 (1996).
[10] W. R. Tribe, M. J. Steer, D. J. Mowbray, M. S. Skolnick, A. N. Forshaw, J. S. Roberts, G. Hill, M. A. Pate, C. R. Whitehouse, and G. M. Williams, Appl. Phys. Lett. **70**, 993 (1997).
[11] W. Wegscheider, L. Pfeiffer, K. West, and R. Leibenguth, Appl. Phys. Lett. **65**, 2510 (1994).