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Carrier transfer between V-grooved quantum wire and vertical quantum well

W. Lu [a], X.Q. Liu [a], Z.F. Li [a], S.C. Shen [a], Q.X. Zhao [b,*], Y. Fu [b], M. Willander [b], H.H. Tan [c], C. Jagadish [c], J. Zou [d], D.J.H. Cockayne [d]

[a] *National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 420 Yudian Road, Shanghai 200083, China*

[b] *Microelectronics Center at Chalmers, Physical Electronics and Photonics, Department of Physics, University of Gothenburg and Chalmers University of Technology, Fysikgränd 3, S-412 96 Gothenburg, Sweden*

[c] *Department of Electronic Material Engineering, Research School of Physical Science and Engineering, The Australian National University, Canberra, ACT 0200, Australia*

[d] *Electron Microscope Unit and Australian Key Center for Microscopy and Microanalysis, The University of Sydney, Sydney, NSW 2006, Australia*

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Abstract

We report the temperature dependence of the photoluminescence from our V-grooved GaAs/AlGaAs quantum wires. Based on the specially resolved luminescence results, our results show that in the processes of real space carrier transfer from the vertical quantum well region to quantum wire region, a 3.5 meV thermal activation energy has been experimentally observed in our sample. The thermal activation is attributed as the scattering process of carriers from two-dimensional states in the vertical quantum well to the one-dimensional quantum wire states. Based on numerical energy band structure analysis, a thermal activation energy of 2–9 meV is obtained theoretically, in good agreement with the experimental data. © 2001 Elsevier Science B.V. All rights reserved.

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The great success of electron and hole confinements in two-dimensional (2D) quantum well systems [1,2] excites further interest in the even-lower-dimensional systems, i.e., quasi-one-dimensional (1D) [3,4] and quasi-zero-dimensional (0D) semiconductor structures [5]. In comparison with the bulk (three-dimensional, 3D) and 2D semiconductors, the quantum wire (QWR) system exhibits stronger oscillations at the energy bandedges in its density of states. And its reduced density of states due to extra one-dimensional quantum confinement as compared with 2D quantum well results in a population inversion at a lower threshold current. Recently, low-threshold GaAs QWR laser has been demonstrated by Kapon [3] and Tiwari [6] using epitaxial growth on V-grooved substrate.

Because of the small active volume in QWR device, a highly efficient process of carrier trapping into the QWR region becomes crucial for laser operation [7].

* Corresponding author.
E-mail address: zhao@fy.chalmers.se (Q.X. Zhao).

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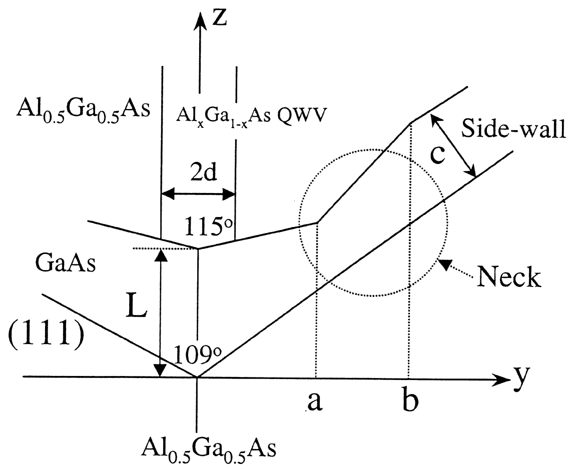

Fig. 1. The geometric structure of the QWR (not to scale). Geometric parameters of the QWR system are determined from TEM: $L = 20$, $c = 14$, $a = 150$, $b = 300$, and $d = 45$ Å.

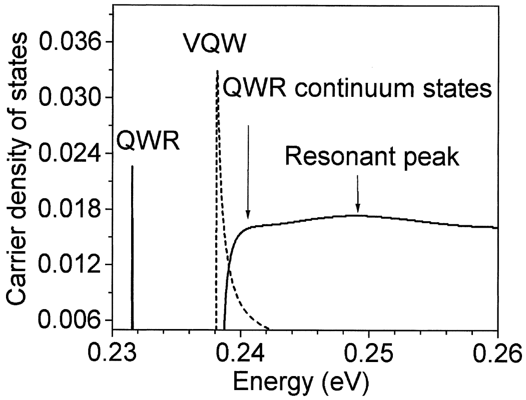

Fig. 2. Electron local densities of states at QWR region $(y, z) = (0, 2)$ Å with solid line and at VQW region $(y, z) = (0, 300)$ Å with dash line.

In the self-organized growth process, free carriers in the crescent-shaped wire at the bottom of the V-groove are laterally confined by either the bulk AlGaAs barrier or GaAs/AlAs multiple quantum wells. When the bulk AlGaAs barrier is used for the lateral confinement for QWR carriers, a vertical quantum well (VQW) normally forms in the AlGaAs alloy at the bottom of the V-groove due to the segregation of the group III species [8] (Fig. 1). Theoretical studies have indicated that carrier transport from the 3D states in the bulk AlGaAs barrier into the VQW is very fast. The carriers are then scattered into QWR where they relax rapidly to the bandedge. This VQW enhancement on the carrier trapping rate of QWR is superior to the GaAs/AlAs superlattice barriers grown by molecular beam epitaxy [7].

Although there have been quite a lot of studies on the carrier scattering behavior [9,10], it is much interesting to study experimentally the carrier transport process between QWR and VQW regions. In this Letter we describe the results of carrier trapping process in QWR on V-grooved substrate which contains a VQW structure in the AlGaAs barrier. Our results indicate that at low temperature the photoluminescence (PL) from QWR is dominated by the carriers transferring from VQW by overcoming a thermal active energy.

We investigate a GaAs QWR that were grown by metal organic vapor phase epitaxy (MOVEP) in V-grooved channels etched on GaAs (100) semi-insulating substrate. A detail description has been reported early [11,12]. The cross section of the $GaAs/Al_{0.5}Ga_{0.5}As$ QWR sample was studied by transmission electron microscopy (TEM) [11] and the spatially resolved luminescence at room temperature has been performed to attribute the luminescence peaks to micro-structures in the sample [12]. The structure is shown schematically in Fig. 1 where the geometric parameters are obtained from the TEM measurement. In our sample, the VQW in the AlGaAs barrier is clearly observed in our early report [12] similar with that on other MOVPE samples [3]. The width of the VQW is about 9 nm with a mole fraction of Al about 0.25 which are estimated from the energy positions of the PL peaks from VQW.

Since the carrier transition process between QWR and VQW depends critically on the energy levels, we first determine the energy levels in the 2D structure shown in Fig. 1. Based on two-dimensional Schrödinger equation in the effective mass approximation, we calculate the local density of states by the recursion method [13,14]. The local density of states is obtained from the local Green's function. It is the sum of the amplitudes of the degenerate states at a spatial point. In Fig. 2 we present the local densities of states in the central of QWR and VQW. We observe two kinds of energy states in the system: a set of discrete sublevels localized in the QWR region (there is only one discrete electronic sublevel in the present QWR structure) and a set of continuum states in both

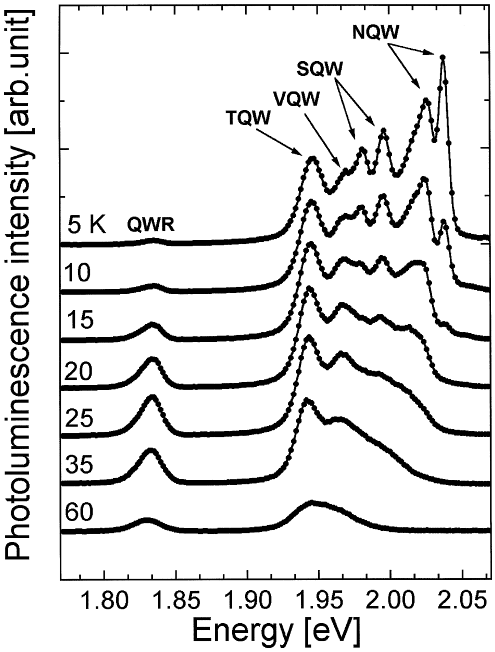

Fig. 3. Temperature-dependent photoluminescence spectra. The dots correspond to measurement data and the solid lines are obtained from fitting process.

the QWR and VQW regions. All the energy states are relative to the GaAs conduction band edge.

The discrete electronic state in QWR is confined by the (111) and $(1\bar{1}1)$ surfaces. The electron will be finally trapped on this state in QWR followed by recombination. The continuum states in the QWR starts at 241 meV, 2 meV above the ground state of VQW. A resonant peak is obtained in the electron continuum states, which is about 9 meV above the ground state of VQW. The qualitative indication of the strength of the trapping process can be obtained from the spatial overlap of VQW and QWR states [7,9]. According to the local density of states in Fig. 2, one can expect a electron state in the energy range from 241 to 128 meV will have strong spatial overlap of VQW and QWR states. So in the scattering process between QWR and VQW, there is thermal active energy E_v in the region of 2–9 meV. In the temperature region of 5–60 K the thermal active diffusion will be dominated by thermally activation energy E_v.

The temperature dependence of the PL from our V-grooved QWR structure is investigated to check the thermal active energy. The photoluminescence spectra

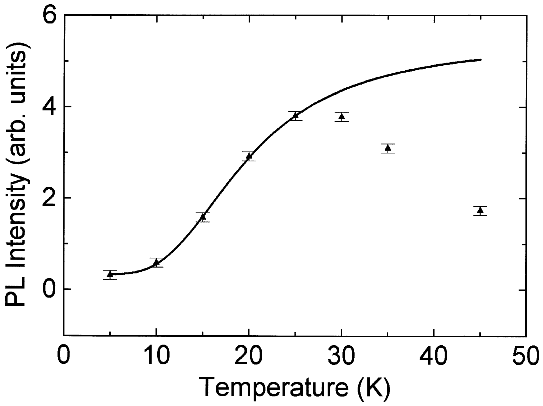

Fig. 4. Temperature dependence of the intensity of QWR photoluminescence. Triangle points: measurement data, the error bars are also presented. Solid line: fitting.

were measured in a temperature range from 5 to 60 K using the 514.5 nm line of an Ar^+ laser as excitation. The PL spectra and their temperature dependence are presented in Fig. 3. The solid lines are the Gaussian curves fitting and the experimental data are presented by dos. Comparing with the room temperature of the micro-PL spectra in our early report [12], the peaks between those at low temperature and room temperature can be well correlated by an energy shift of about 80 meV which is same as the band gap shift of GaAs from 5 to 300 K. So the peaks labeled as NQW, SQW, VQW, TQW and QWR are from neck region, side-wall quantum well, VQW, top-wall quantum well and quantum wire, very similar with the early report [3,15]. Similar with the normal narrow quantum well structure, the doublet of the PL peaks labeled as NQW and SQW is due to the monolayer fluctuation in the quantum well width. The weak PL peak around 1.83 eV at 5 K is the PL from QWR in good agreement with our theoretical value of 1.84 eV. As shown in Fig. 3, there is about 45 times increase of the QWR PL intensity from 5 to 30 K followed by a rapid decay. It is more clearly presented in Fig. 4 as triangle points with error bars. As discussed in the following text, the strong QWR PL intensity increase behavior reflects the enhancement of scattering rate from VQW to QWR. So in our sample, the carriers trapped from VQW has dominated in the total amount of carriers in QWR at 30 K, which shows that an optimization of the VQW is very important for the laser application of V-grooved QWR. The rapid intensity decay is from the non-radiative recombination quenching.

The temperature dependence of the emissions is mainly influenced by the activation and tunneling process. Relative to the carrier transfer contribution from VQW to QWR, in our structure the tunneling between the side-wall quantum wells and QWRs is strongly reduced by the neck region due to high energy barrier as observed in our PL spectra; the neck region volume is only about 0.3% of VQW; the total scattering rate for the direct transferring of carriers from barrier region to QWR region is at least 5 times smaller than that from the VQW [7]. So in our experimental temperature region, it is reasonable to consider the VQW as a dominant the channel for carrier transferring to QWR. By the kinetic model [16] the wire luminescence intensity can be expressed as

$$I = g_r + \frac{g_v}{1 + p_v(T)}, \quad p_v(T) \propto T^{-3/2} e^{E_v/k_B T}, \quad (1)$$

where g_v and g_r are the generation rate in VQW and wire region, respectively. T is temperature and E_v is the thermal active energy for carriers transfer from VQW to QWR. In order to avoid the non-radiative recombination induced thermal quenching effect, only data below 30 K are used when fitting the wire luminescence intensity. We obtain the thermal activation energy to be $E_v = 3.5$ meV ($g_v = 1.3$, $g_r = 0.084$). The fitting curve is shown as the solid line in Fig. 4, in good agreement with experimental data. This experimental thermal activation energy agrees well with the theoretical value E_v in the range of 2–9 meV.

At very low temperature, e.g., $T = 5$ K, all the activation transfer processes freeze out almost completely. Then the ratio of the luminescence intensity will simply proportional to the generation rate. By fitting the PL spectrum at 5 K, we obtain the luminescence intensity ratio between VQW and QWR is 13.6. Meanwhile, from the fitting in Fig. 4 we have $g_v/g_r = 15.5$. They are in good agreement with each other.

In conclusion, we have reported experimental study of the carrier transfer process from VQW to QWR in GaAs V-grooved structure. We find that the thermally activation energy in this transfer process in our sample is 3.5 meV experimentally and 2–9 meV theoretically, and is explained by the strong overlap of electron states in QWR and VQW.

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References

[1] L. Esaki, R. Tsu, IBM J. Res. Develop. 14 (1970) 61.
[2] B.F. Levine, J. Appl. Phys. 74 (1993) R1.
[3] E. Kapon, D.M. Hwang, R. Bhat, Phys. Rev. Lett. 63 (1989) 430.
[4] M. Walther, E. Kapon, C. Caneau, D.M. Hwang, L.M. Schiavone, Appl. Phys. Lett. 62 (1992) 2170.
[5] M.A. Kastner, Phys. Today 24 (1993).
[6] S. Tiwari, G.D. Petit, K.R. Milkove, F. Legoues, R.J. Davis, J.M. Woodall, Appl. Phys. Lett. 64 (1994) 3536.
[7] C. Kiener, L. Rota, A.C. Maciel, J.M. Freylan, J.F. Ryan, Appl. Phys. Lett. 68 (1996) 2061.
[8] A. Gustafsson, F. Reinhardt, G. Biasiol, E. Kapon, Appl. Phys. Lett. 67 (1995) 3673.
[9] J.F. Ryan, A.C. Maciel, C. Kiener, L. Rota, K. Turner, J.M. Freyland, U. Marti, D. Martin, F. Morier-Gemound, F.K. Reinhart, Phys. Rev. B 53 (1996) R4225.
[10] A. Venu Gopal, R. Kumar, A.S. Vengurlekar, T. Melin, F. Laruelle, B. Etienne, Appl. Phys. Lett. 74 (1999) 2474.
[11] X.Q. Liu, W. Lu, X.S. Chen, S.C. Shen, H.Z. Wang, F.L. Zhao, X.G. Zheng, Y. Fu, M. Willander, Study of carrier relaxation process of V-grooved AlGaAs/GaAs quantum wire modified by selective implantation induced intermixing, in: SPIE Photonics West, San Jose, CA, 23–29 January, 1999.
[12] X.Q. Liu, W. Lu, Z.F. Li, Y.D. Chen, S.C. Shen, Y. Fu, M. Willander, H.H. Tan, S. Yuan, C. Jagadish, J. Zou, D.J.H. Cockayne, Appl. Phys. Lett. 75 (1999) 3339.
[13] Y. Fu, M. Karlsteen, M. Willander, Superlatt. Microstruct. 22 (1997) 405.
[14] D.G. Pettifor, D.L. Weaire (Eds.), The Recursion Method and its Application, Springer, Berlin, 1985.
[15] X.L. Wang, M. Ogura, H. Matsuhata, Appl. Phys. Lett. 67 (1995) 3629.
[16] Y. Zhang, M.D. Sturge, K. Kash, B.P. van der Gaag, A.S. Gozdz, L.T. Florez, J.P. Harbison, Phys. Rev. B 51 (1995) 13303.