AIP | Journal of Applied Physics

Evidence of blocking effect on carrier trapping process by necking region in very narrow AlGaAs/GaAs V-grooved quantum wire structure

X. Q. Liu, A. Sasaki, N. Ohno, Z. F. Li, W. Lu, S. C. Shen, Y. Fu, M. Willander, H. H. Tan, and C. Jagadish

Citation: Journal of Applied Physics **90**, 5438 (2001); doi: 10.1063/1.1410317
View online: http://dx.doi.org/10.1063/1.1410317
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/90/10?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS VOLUME 90, NUMBER 10 15 NOVEMBER 2001

COMMUNICATIONS

Evidence of blocking effect on carrier trapping process by necking region in very narrow AlGaAs/GaAs V-grooved quantum wire structure

X. Q. Liu[a)]
Academic Frontier Promotion Center, Osaka Electro-Communication University, Neyagawa, 572-8530, Japan and National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, People's Republic of China

A. Sasaki and N. Ohno
Academic Frontier Promotion Center, Osaka Electro-Communication University, Neyagawa, 572-8530, Japan

Z. F. Li, W. Lu, and S. C. Shen
National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, People's Republic of China

Y. Fu and M. Willander
Physical Electronics and Photonics, Department of Physics, Fysikgrand 3, University of Goteborg and Chalmers University of Technology, S-412 96 Goteborg, Sweden

H. H. Tan and C. Jagadish
Department of Electronic Material Engineering, Research School of Physical Science and Engineering, Australian National University, Canberra, ACT 0200, Australia

(Received 16 January 2001; accepted for publication 19 August 2001)

Transient band-gap renormalization (BGR) effects are investigated in AlGaAs/GaAs V-grooved quantum structures. The temperature-dependent transient BGR effects in the sidewall quantum well (SQWL) provide direct evidence of the existence of the blocking effect by the necking region barrier on the carrier trapping process. These effects provide a useful method to show the existence of the necking region, particularly for very thin SQWL structures. The temperature-dependent lifetimes of the SQWL and quantum wire (QWR) provide further proof of the carrier trapping process from the SQWL to the QWR. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1410317]

V-grooved quantum wire (QWR) structures have attracted much attention in recent years[1–7] due to the simplicity of their fabrication and prospects for device applications. The V-grooved QWR is fabricated by direct epitaxial growth on a V-grooved substrate. However, the V-grooved structures become rather complicated near the QWR since the growth occurs on (100), (111), and (311) facets. Different growth modes interact very strongly with each other during growth, and this interaction simultaneously forms different kinds of low dimensional structures, such as (111)A sidewall quantum well (SQWL), vertical quantum well (VQWL), (100) QWR, and (311) necking region.

The lateral confinement of QWR is caused by the necking region. At the same time the necking region blocks the carrier transfer from the SQWL to the QWR region. Photoluminescence (PL) from the necking region has been observed at room temperature using micro-PL.[8] For device applications, investigation of carrier trapping into the wires from the adjacent quantum structures is strongly required. In this article, the blocking effect on the carrier trapping process from the SQWL to the QWR caused by the necking region is directly shown by the obvious transient band-gap renormalization (BGR) in the SQWL at low temperatures, which is caused by high carrier density.[9–11] This effect can be used to directly determine whether the necking region exists or not, particularly for very thin well structures, in which the necking region may not be directly observable on a transmission electron microscopy (TEM) image.

A semi-insulating GaAs (100) substrate was processed using standard photolithography and wet etching. Fifty periods of 2 μm wide stripes and 2 μm spacing was used to create 4 μm-periodic V grooves. After the pattern transfer, a sawtooth-type surface profile (about 2.5 μm depth) was formed by wet chemical etching ($H_3PO_4:H_2O_2:H_2O=1:1:3$) at 0 °C. The V grooves were aligned along the [0-11] direction. Before being loaded into the growth chamber, the V-grooved substrate was cleaned with warm trichloroethylene, acetone, and methanol, and then trimly etched with $H_2SO_4:H_2O_2:H_2O(=20:1:1)$ for 20 s. The substrate was heated to 800 °C under an AsH_3 atmosphere to desorb the oxide layer on the surface. The 1 μm $Al_{0.5}Ga_{0.5}As$ layer was grown following the 0.1 μm GaAs buffer layer. A nominated 1 nm GaAs well layer was deposited followed by a 0.1

[a)] Electronic mail: xqliu@etl.go.jp

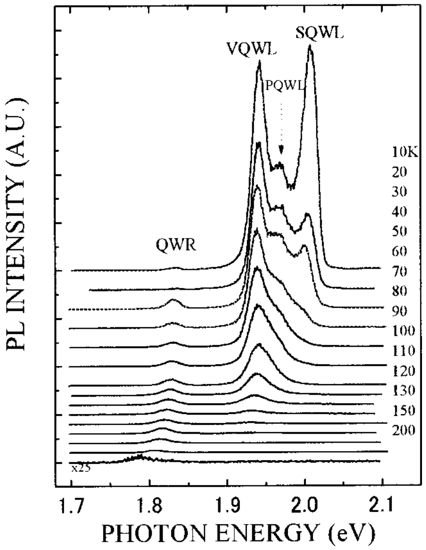

FIG. 1. Temperature-dependent PL spectra. At 10 K, four peaks located at 617, 630, 639, and 676 nm are labeled as SQWL, PQWL, VQWL, and QWR, respectively.

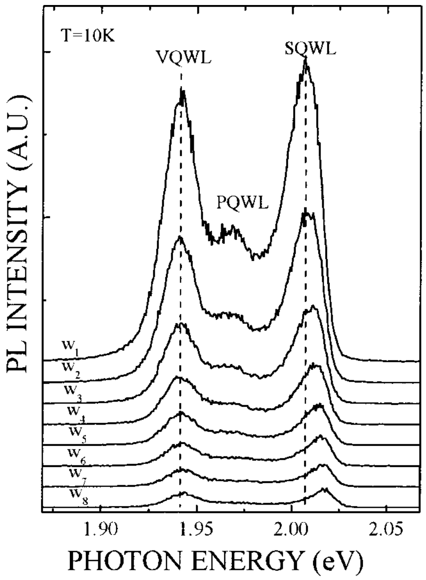

FIG. 2. Eight window time-delayed PL spectra at 10 K labeled as w_1 w_2, w_3,...,w_8.

μm $Al_{0.5}Ga_{0.5}As$ top barrier layer. Finally, a 200 nm GaAs top layer was grown. All layers were grown at 750 °C.

The time-resolved PL (TRPL) measurements were performed using a streak camera in conjunction with a 25 cm monochromator equipped with a 100 lines/mm grating. A 400 nm pulse laser line, which is double the frequency of the Al_2O_3:Ti laser pumped by the Ar^+ laser, was used as the excitation source. The repetition rate of the source was 2 MHz with a pulse width of 1.5 ps. The laser power was 0.46 mW with a spot diameter of 0.1 mm on a sample after focusing, which corresponds to an energy density of 1.4 μJ/cm^2 per pulse. The spectral resolution is about 0.3 nm, which is well below the linewidth of the PL. Samples were mounted to the cold finger of a helium-cycled cryostat where the temperature can be changed from 10 to 300 K.

Figure 1 shows the temperature dependent time-integrated PL spectra. At 10 K, four peaks are clearly observed located at 617, 630, 639, and 676 nm, which are attributed to the PL of the SQWL, planar QWL (PQWL), VQWL, and QWR, respectively. PQWL is the planar part QWL, which is between the two 50-period wire regions. VQWL is the low Al part at the central region of the V groove of the AlGaAs barrier layers, which is formed due to different diffusion lengths of Al and Ga atoms. The width of the VQWL is about 12 nm. Figure 1 shows that the PL intensity of SQWL is very strong at low temperatures (lower than 30 K), while it decreases quickly at temperatures higher than 30 K. The stronger PL intensity of the SQWL at low temperatures indicates that carriers cannot be trapped into the QWR efficiently within the recombination time in a SQWL. Two kinds of barriers may block the carriers from trapping into the wire region. One is 1 monolayer (ML) fluctuation-caused barriers in the (111)QWL layer. The carriers will be stored in the potential minima and cannot be trapped into the wire region efficiently at low temperatures. As the temperature increases, the carriers will be thermalized and excited to overcome the barrier. In this case, the SQWL PL peaks will show blueshifts with temperature increasing at low temperature range due to carrier thermalization out of the potential minima.[8] In Fig. 1 no obvious blueshift can be observed as the temperature increases. Thus the 1 ML fluctuation-induced barrier is less pronounced here. The other kind of barrier is the necking region adjacent to the wire region. The necking region forms a barrier to prevent the carriers in SQWL from trapping into the wire region. In this case the necking region would not cause any carrier confinement in the SQWL. The time-delayed PL spectra at low temperature provides direct evidence of the blocking effect of the necking region on the carrier trapping process.

Figure 2 demonstrates the eight windows time-delayed PL spectra at 10 K. Obvious blueshifts can be observed, with a maximum 10 meV from the first window w_1 to the eighth window w_8 at 10 K. These obvious blueshifts result from the BGR effect,[9–11] which occurs when the dense electron–hole plasma forms in the QWL. The transient blueshifts keep appearing until 1.75 ns, i.e., after the exciting pulse, the density of photogenerated carriers is sufficiently high to cause obvious BGR effects in the SQWL. As the carrier density decreases with time, the net BGR value decreases, which causes the blueshifts of the transient PL peaks as shown in Fig. 2 from w_1 to w_8. These transient BGR effects demonstrate that the carrier sin SQWL cannot be trapped in the wire region effectively at 10 K. As temperature increases, the carriers may be thermalized and tunnel through or overcome the necking region barriers. Figure 3 demonstrates the transient transition energy of the SQWL at different temperatures. When the temperature is lower than 30 K, obvious BGR effects can be observed. Thus the carriers cannot be trapped in the wire region effectively within 30 K. As the temperature grows higher than 40 K. The BGR effects disappear. In this case, carriers can be trapped into the wire region effectively, and the PL intensity of the SQWL decreases dramatically. According to the experimental results in Ref. 8, the barrier caused by the necking region is about 16 meV, which

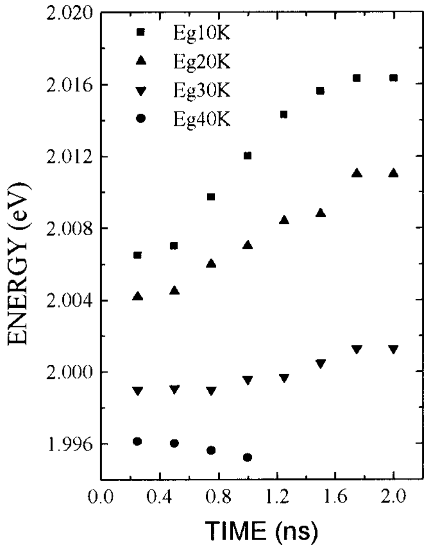

FIG. 3. Transient transition energies at different temperatures. Eg10K, Eg20K, Eg30K, and Eg40K stand for the transition energies at 10, 20, 30, and 40 K, respectively.

is larger than the thermal energy at 40 K (4 meV). Therefore the carriers become trapped in the wire region mainly by tunneling through the necking barrier.

The temperature-dependent lifetimes of the SQWL and QWR also provide further proof of the carrier trapping process, which is blocked by the necking region. The temperature-dependent lifetimes of the SQWL and QWR are shown in Fig. 4. The inset shows the time decay curves at different temperatures. The lifetime is 0.32 ns at 10 K, which is a typical QWL lifetime. At temperatures higher than 40 K, the lifetimes are much shorter: 0.1 and 0.07 ns for 40 and 50 K, respectively. When temperature rises beyond 60 K, the PL of the SQWL disappears. In the meantime, the lifetime of the QWR increases with temperature and reaches the maximum at 60 K. This indicates that the radiative recombination process is dominant within 60 K. Although the nonradiative recombination in the SQWL may also contribute to shortening the lifetime, the above increase of QWR lifetimes within 60 K indicates that the process of carrier trapping in the wire region is dominant. When the temperature is higher than 60 K, the carrier will be trapped in the wire region very efficiently. This may be important for device applications. Of course the nonradiative recombination in the SQWL will also compete with the trapping process as the temperature increases.

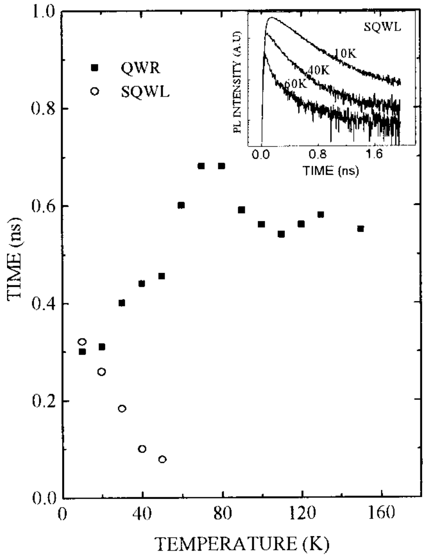

FIG. 4. Temperature-dependent carrier lifetimes in the QWR and SQWL. Inset shows the PL decay curves of the SQWL at different temperatures.

In conclusion, temperature-dependent transient BGR effects in the SQWL were investigated providing direct evidence of the existence of the blocking effect caused by the necking region barrier on the carrier trapping process. At temperatures lower than 40 K, obvious BGR effects were observed in the SQWL because the carriers were prevented from trapping into the wire region by the necking region barrier. This BGR effect could constitute direct proof of the existence of the blocking barrier caused by the necking region. It provided a useful method to determine the existence of the necking region, particularly for the very thin SQWL structure of which the TEM image could not provide a clear image. As well the thinner SQWL structure may cause stronger BGR effects.[9,10] The temperature-dependent lifetimes of the SQWL and the QWR provided further proof of the carriers trapping process.

This work was supported in part by a grant from the Academic Frontier Promotion Project of Monbusho, Shanghai “QiMingXing” Fund No. 98QA14004, the State Key Program for Basic Research of China, and the AusAID through IDP Education Australia under Australia-China Institutional Links Program.

[1] E. Kapon, D. W. Hwang, and R. Bhat, Phys. Rev. Lett. **63**, 430 (1989).
[2] T. G. Kim, X. L. Wang, K. Komori, K. Hikosaka, and M. Ogura, Electron. Lett. **35**, 639 (1999).
[3] X. L. Wang, M. Ogura, and H. Matsuhata, Appl. Phys. Lett. **66**, 1506 (1995).
[4] J. Bellessa, V. Voliotis, R. Grousson, X. L. Wang, M. Ogura, and H. Matsuhata, Phys. Rev. B **58**, 9933 (1998).
[5] X. L. Wang, M. Ogura, and H. Matsuhata, J. Cryst. Growth **195**, 586 (1998).
[6] X. Q. Liu, W. Lu, X. S. Chen, S. C. Shen, H. H. Tan, S. Yuan, C. Jagadish, M. B. Johnston, L. V. Dao, M. Gal, J. Zou, and D. J. H. Cockayne, J. Appl. Phys. **87**, 1566 (2000).
[7] X. Q. Liu, A. Sasaki, N. Ohno, X. L. Wang, and M. Ogura, Appl. Phys. Lett. **77**, 1481 (2000).
[8] 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, and D. J. H. Cockayne, Appl. Phys. Lett. **75**, 3339 (1999).
[9] G. Trankle, H. Leier, A. Forchel, H. Haug, C. Ell, and G. Weimainn, Phys. Rev. Lett. **58**, 419 (1987).
[10] S. D. Sarma, R. Jalabert, and S. R. E. Yang, Phys. Rev. B **39**, 5516 (1989); **41**, 8288 (1990).
[11] R. Cingolani, H. Kalt, and K. Ploog, Phys. Rev. B **42**, 7655 (1990).