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## Abstract

Low-temperature photoluminescence (PL) measurements on pseudomorphic modulation-doped transistors with a low-temperature (LT) GaAs layer in the GaAs buffer layer clearly show a decrease in the quantum-well/PL transition energies compared to a structure with no LT GaAs. Self-consistent calculations of the electron and hole band structure confirm that the observed increase in the redshift in PL energies with increasing quantum-well/LT-GaAs spacing can be attributed to band bending induced by the Fermi level pinning at the undoped-GaAs/LT-GaAs interface.

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# Introduction

Recently there has been much interest in the properties [1], device applications [2,3], and mechanism [4–8] of high-resistivity low-temperature GaAs (LT GaAs), which is grown by molecular beam epitaxy with a substrate temperature of around 200 to 300 °C. LT GaAs contains a high concentration of arsenic antisite defects ($As_{Ga}$), which act as nonradiative recombination centers [5–7]. Consequently, LT GaAs exhibits a weak photoluminescence (PL) [1] and a subpicosecond electron-hole recombination time [9]. Recently we published the results of LT PL measurements on a number of pseudomorphic high-electron-mobility transistor (PHEMT) structures, which have an LT-GaAs layer embedded in the nominally undoped GaAs buffer layer at various depths below the quantum well (QW) [10]. Our results clearly showed a decrease in the PL energy (redshift) of the PHEMTs with LT GaAs, due to the quantum-confined Stark effect [11] and a novel band-bending effect of LT GaAs.

In this report we present the results of self-consistent modeling of this band-bending effect for the PHEMT structures, taking into account the Fermi level pinning at the interface between the normal-temperature not intentionally doped (NID) GaAs and the LT GaAs. Calculations of the electron and hole subband energies indicate that the redshift (decrease) in PL energy, which increases with the LT-GaAs/QW separation, can be explained by the variations in the electric field in the NID GaAs due to pinning of the Fermi level at the NID-GaAs/LT-GaAs interface.

# Experimental Results

The PHEMTs used in this study were grown by molecular beam epitaxy on semi-insulating GaAs. The PHEMT heterostructure consists of the following layers:

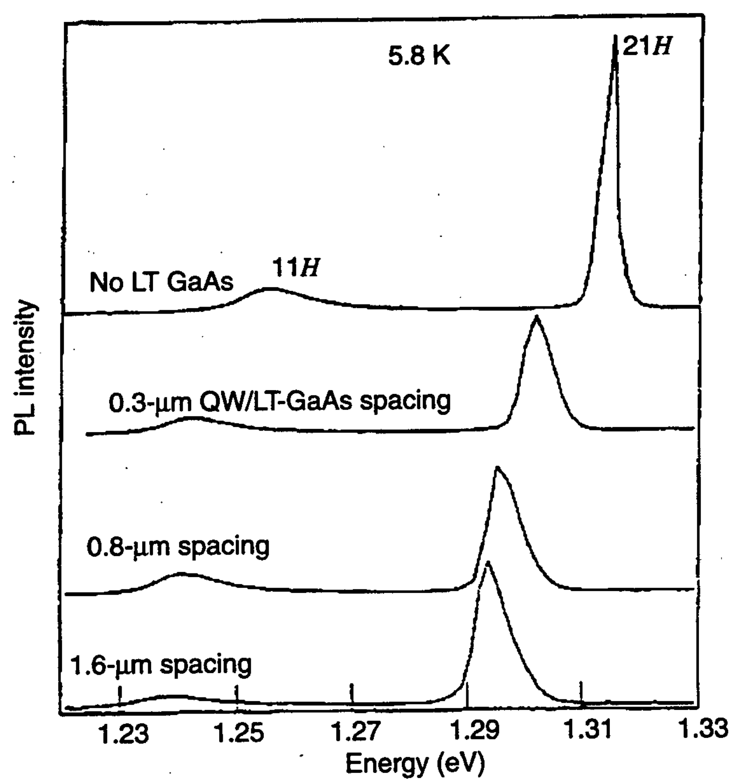
- 4000 Å of NID GaAs grown at 600 °C,
- 4000 Å of LT-GaAs grown at 220 °C,
- a layer of NID GaAs grown at 600 °C whose thickness *d* varies for different samples,
- 150 Å of $In_{0.2}Ga_{0.8}As$,
- 50 Å of undoped $Al_{0.3}Ga_{0.7}As$,
- 100 Å of Si-doped ($6 \times 10^{18}$ cm$^{-3}$) $Al_{0.25}Ga_{0.75}As$,
- 200 Å of undoped $Al_{0.25}Ga_{0.75}As$, and
- 200 Å of Si-doped ($2 \times 10^{18}$ cm$^{-3}$) GaAs.

A control PHEMT was grown without any LT GaAs; instead it has a 1-µm NID-GaAs buffer, which was grown at 600 °C. Note that the LT GaAs is annealed by the growth of the subsequent layers at 600 °C. Sheet resistance and Shubnikov-de Haas (SdH) measurements show that the two-dimensional electron gas (2DEG) density $n_s$ and drift mobility are not degraded by the inclusion of the LT GaAs in the buffer, in agreement with previous results [12]. At 300 K, the measured $n_s$ is $1.9 \times 10^{12}$ cm$^{-2}$, and the measured electron mobility is 6000 cm$^2$/Vs. The 2DEG mobility at 4.2 K for the PHEMTs with LT GaAs ranges from $2.7 \times 10^4$ to $8.3 \times 10^4$ cm$^2$/Vs. The SdH measurements also confirm that the $n = 2$ conduction subband of the InGaAs QW is occupied for all samples. The measured electron density in the second subband is $1 \times 10^{11}$ cm$^{-2}$ for the structure with no LT GaAs and approximately $2 \times 10^{11}$ cm$^{-2}$ for the structures with LT GaAs. PL measurements were carried out with the samples mounted in a variable-temperature liquid helium cryostat. The 5145-Å emission from an argon ion laser was used to excite the structures with excitation intensity of about 1 W/cm$^2$. The PL spectrum was measured with a 1-m monochromator and a germanium photodetector.

Figure 1 shows the 5.8 K PL spectra for structures with QW/LT-GaAs spacings of 0.3, 0.8, and 1.6 µm and for the structure with no LT-GaAs layer. The observed PL spectrum of the sample without the LT GaAs at 5.8 K shows a 16-meV-wide (full width at half maximum) asymmetric feature having a peak at 1255 meV, and a relatively sharp feature at 1315 meV having a width of 3 meV and an integrated PL intensity that is a factor of approximately 3 greater than that of the 1255-meV peak. Two observations—the difference between the low-energy and the high-energy peaks and the dependence of the PL on the electric field of the NID-GaAs buffer layer—lead us to conclude that the observed PL can be attributed to the recombination of $n = 1$ and $n = 2$ subband electrons from the degenerate 2DEG with $m = 1$ heavy holes in the InGaAs QW. The low-energy PL feature (designated 11*H*) is attributed to the transition of $n = 1$ electrons to $m = 1$ heavy holes. The high-energy PL feature (designated 21*H*) is attributed to the transition of $n = 2$ electrons to $m = 1$ heavy holes. The width of the 11*H* PL feature is broadened by indirect recombination processes, which are facilitated by the scattering of carriers in the QW by ionized impurities in the doped AlGaAs barrier [13]. The relatively large peak intensity, sharp symmetric lineshape, and narrow width of the 21*H* PL feature suggest that this feature has a strong component from the recombination of $n = 2$ subband excitons.

These data show that the structures with an LT-GaAs layer exhibit a redshift in their PL transition energies. The 11*H* and 21*H* PL energies decrease with increasing QW/LT-GaAs spacing *d*, for spacings up to 1.6 µm. Note that the shift in transition energy seems to approach an asymptote at $d \approx 1.6$ µm, as shown in figure 1. When the structure with $d = 1.6$ is compared to the structure without LT GaAs, the observed red-shifts of the 11*H* and 21*H* PL energies are 17.3 and 21.7 meV, respectively. Figure 1 shows that for structures with an LT-GaAs layer, the 21*H* PL lineshape is asymmetric with a linewidth of ≈6.2 meV, compared to a linewidth of 3 meV for the sample without LT GaAs. In contrast, the width and line shape of the 11*H* PL are the same for all the structures.

**Figure 1. PL spectra from structure with no LT GaAs and structures with QW/LT-GaAs spacing of 0.3, 0.8, and 1.6 µm. Spectra have been shifted along vertical axis for visual clarity.**



# Theory

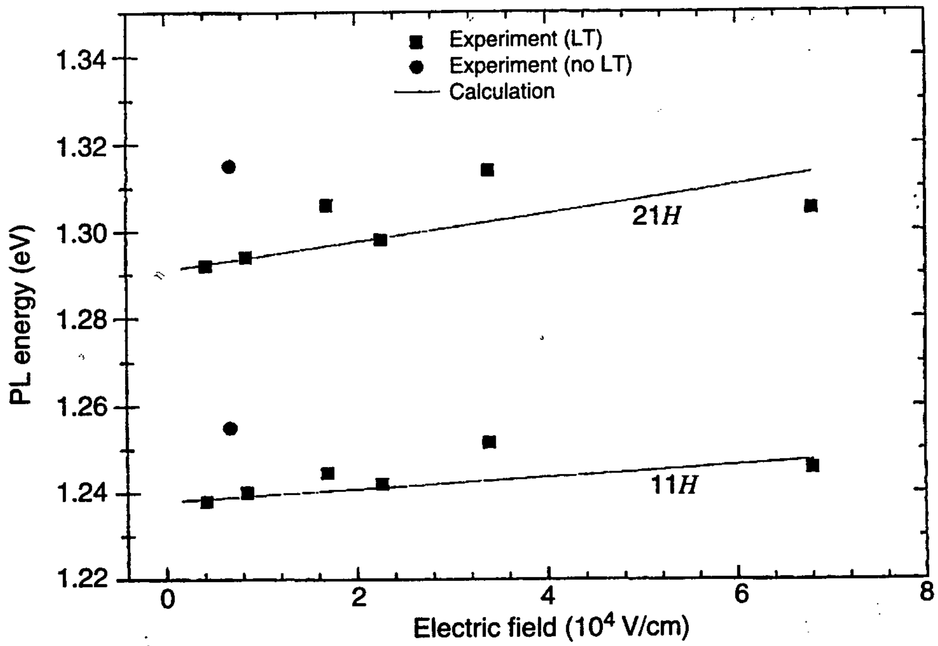
We carried out self-consistent Schrödinger-Poisson calculations of the conduction and valence band energy levels and distribution of charge in this heterostructure using the boundary condition that at the NID-GaAs/LT-GaAs interface the Fermi level is pinned at 0.7 eV below the conduction band [14]. In our calculations the primary effect of the LT-GaAs layer is modeled by the Fermi level pinning at the NID-GaAs/LT-GaAs interface. We assume that the background doping in the NID GaAs is negligible, which means that the electrostatic electric field is constant across the NID-GaAs layer adjacent to the InGaAs QW. This electric field boundary condition varies for the different structures because of the variation in $d$. For the structure without an LT-GaAs layer, the electric field boundary condition is given by the midgap pinning of the Fermi level at the NID-GaAs/semi-insulating-GaAs substrate interface. We use the Hartree approximation for the valence band calculation, taking into account the increased bandgap of the strained InGaAs layer [15]; this calculation did not include many-body effects.

Our calculations confirm that the $n = 1$ and $n = 2$ conduction subbands are occupied, and good agreement with the magnetotransport-determined electron densities is obtained if the effective AlGaAs doping is $4 \times 10^{18}$ $cm^{-3}$. The calculated PL energies and oscillator strengths verify that we have observed the $11H$ and $21H$ transitions. We obtained excellent agreement between the observed and calculated values of $11H$ and $21H$ energies using the published strained bandgap renormalization parameters [15]. Our calculations confirm that, in comparison to the conduction subbands, the $m = 1$ hole subband energy is insensitive to changes in the electric field in the NID GaAs.

Figure 2 shows the theoretical and experimental values of the $11H$ and the $21H$ PL energies as a function of the electric field in the NID GaAs. As confirmed by the good agreement between theory and experiment for the structures with LT GaAs, the observed decrease in the transition PL energies as $d$ increases can be attributed to the quantum-confined Stark effect (QCSE), which has been observed before in undoped QWs in a *p-i-n* structure [11]. For our modulation-doped PHEMTs, the QCSE is caused by two opposing electric fields in the structure: the self-consistent electric field at the AlGaAs/InGaAs interface and the electric field in the NID-GaAs layer adjacent to the QW. The Fermi level pinning at the NID-GaAs/LT-GaAs interface results in a sample-to-sample variation of the electric field in the NID-GaAs layer, resulting in a blueshift in the $11H$ and $21H$ PL energies with increasing electric field in the NID GaAs.

The present theoretical model does not explain the large observed $11H$ and $21H$ PL energies of the sample with no LT GaAs. This disagreement could be due to a large error in the thickness of the NID-GaAs layer, a variation in the InGaAs composition, or a complicated doping profile in the NID GaAs and the semi-insulating GaAs buffer layers of the sample with no LT GaAs. Further experimental and possibly more theoretical work is needed to resolve this discrepancy.

Figure 2. Calculated and experimental 11*H* and 21*H* PL energies as a function of electric field in NID GaAs.



# Conclusion

In summary, low-temperature photoluminescence measurements on pseudomorphic modulation-doped transistors with a low-temperature GaAs layer in the GaAs buffer layer clearly show a decrease in the quantum-well PL transition energies compared to a structure with no LT GaAs. Self-consistent calculations of the electron and hole band structure confirm that the observed increasing redshift in PL energies with increasing QW/LT-GaAs spacing can be attributed to band bending induced by the Fermi level pinning at the NID-GaAs/LT-GaAs interface. These results are relevant to high-speed electronic and optoelectronic semiconductor devices, which use LT-GaAs buffer layers.

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# References


1. F. W. Smith, A. R. Calawa, C.-L. Chen, M. J. Manfra, and L. J. Mahoney, IEEE Electron Devices Lett. **9**, 77 (1988).
2. P. M. Solomon, S. L. Wright, and F. J. Canora, IEEE Electron Devices Lett. **12**, 117 (1991).
3. B. J.-F. Lin, C. P. Kocot, D. E. Mars, and R. Jaeger, IEEE Trans. Electron Devices **37**, 46 (1990).
4. M. Kaminska, Z. Liliental-Weber, E. R. Weber, T. George, J. B. Kortright, F. W. Smith, B.-Y. Tsaur, and A. R. Calawa, Appl. Phys. Lett. **54**, 1881 (1989).
5. M. O. Manasrech, D. C. Look, K. R. Evans, and C. E. Stutz, Phys. Rev. B **41**, 10,272 (1990).
6. D. C. Look, D. C. Walters, M. O. Manasrech, J. R. Sizelove, C. E. Stutz, and K. R. Evans, Phys. Rev. B **42**, 3578 (1990).
7. X. Liu, A. Prasad, W. M. Chen, A. Kurpiewski, A. Stoschek, Z. Liliental-Weber, and E. R. Weber, Appl. Phys. Lett. **65**, 3002 (1994).
8. A. C. Warren, J. M. Woodall, J. L. Freeouf, D. Grishchkowsky, D. T. McInturff, M. R. Melloch, and N. Otsuka, Appl. Phys. Lett. **57**, 1331 (1990).
9. J. F. Whitaker, J. A. Valdmanis, M. Y. Frankel, S. Gupta, J. M. Chwalek, and G. A. Mourou, Microelectron. Eng. **12**, 369 (1990).
10. P. A. Folkes, Doran Smith, R. A. Lux, W. Zhou, R. Thompson, R. Moerkirk, and M. Lemeune, Appl. Phys. Lett. **69**, 2234 (1996).
11. D.A.B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegmann, T. H. Wood, and C. A. Burrus, Phys. Rev. B **32**, 1043 (1985).
12. M. R. Melloch, D. C. Miller, and B. Das, Appl. Phys. Lett. **54**, 943 (1989).
13. S. K. Lyo and E. D. Jones, Phys. Rev. B **38**, 4113 (1988).
14. A. C. Warren, J. M. Woodall, P. D. Kirchner, X. Yin, X. Guo, F. H. Pollak, and M. R. Melloch, J. Vac. Sci. Technol. B **10**, 1904 (1992).
15. S. H. Pan, H. Shen, Z. Hang, F. H. Pollak, W. Zhuang, Q. Xu, A. P. Roth, R. Masut, C. LeCelle, and D. Morris, Phys. Rev. B **38**, 3375 (1988).

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