Measurement of the AlGaInAs/AlGaAs conduction-band offset using ballistic electron emission spectroscopy

S. Bhargava, C. Zheng, J. Ko, M. A. Chin, L. A. Coldren, and V. Narayanamurti[a)]
Electrical and Computer Engineering Department, University of California, Santa Barbara, California 93106

(Received 20 July 1998; accepted for publication 30 September 1998)

Ballistic electron emission spectroscopy (BEES) has been used to determine the conduction-band offset between a 10-nm-thick $Al_{0.12}In_{0.22}Ga_{0.66}As$ (Q) strained layer and a ternary $Al_{0.2}Ga_{0.8}As$ (T) barrier located beneath the surface. A three-sample process was used so that the known, reproducible Au/GaAs Schottky barrier would be the top layer of all measured structures. BEES thresholds obtained for Au/GaAs, Au/GaAs/Q, and Au/GaAs/Q/T were 0.96 ± 0.02, 0.98 ± 0.04, and 1.08 ± 0.04 meV yielding offsets of ~20 meV for GaAs/Q and ~100 meV for Q/T. Under the affect of a high-temperature anneal, the Q/T offset was reduced to ~40 meV. In addition, a structure employing solely Au/GaAs/AlGaAs was used to study transitivity for the Q/T material system. © *1998 American Institute of Physics.* [S0003-6951(98)03548-7]

The field of vertical cavity lasers (VCLs) has seen rapid advancements in recent years. Among many possible applications, vertical cavity lasers are especially attractive for low-cost short-distance data links and free-space optical communication. By incorporating aluminum into strained GaInAs quantum well (QW) structures, the emission wavelength can be decreased while still maintaining a desired strain level for potential improvements in device properties.[1–3] The extension of strained QW lasers to shorter wavelengths may provide lower threshold current density and superior reliability over conventional GaAs lasers. The knowledge of conduction-band offsets in the AlGaInAs/AlGaAs material system is important in the design of high-performance 850 nm VCLs that are compatible with GaAs- or Si-based photoreceivers and meet the established data-link standards. Recently, we have obtained a state-of-the-art threshold current of 290 μA from a 5-μm-wide, oxide-apertured VCL using strained AlGaInAs/AlGaAs active layers.[4]

The ballistic electron emission microscope (BEEM) is a three-terminal modification of a scanning tunneling microscope (STM) in which the STM tip, acting as an emitter, injects hot carriers into a thin (<100 Å) Au metal (base) layer deposited on a semiconductor.[5,6] Since the attenuation length of these injected electrons in Au is ~125 Å,[5] many of the carriers will travel ballistically through the metal until they reach the Schottky barrier (SB). Some of the carriers will have sufficient energy and appropriate momenta to overcome the SB and will be collected at the semiconductor contact (collector). BEEM spectroscopy is performed by pausing the STM tip during a topographic scan, and measuring the collector current I_c as a function of the tip–base voltage V_t. When V_t becomes greater than the SB, a threshold in I_c is observed. A key point to note is that during data acquisition, the BEEM's three-terminal capability allows for the energy bands in the metal semiconductor region to remain unchanged. The BEEM has been shown to give accurate measurements of band lineups located spatially beneath the surface.[7,8]

The epitaxial layers were grown on a (100) n^+ GaAs substrate in a Varian Gen II molecular beam epitaxy machine using As_2 as the arsenic source. The growth temperature was 600 °C for the GaAs and AlGaAs layers and lowered to 580 °C for the AlGaInAs layer. All layers in these samples were nonintentionally doped so that any variations caused by the doping would be removed.[9] In addition, all the samples were terminated with a 30 nm GaAs cap layer. After growth, Au was thermally evaporated in 1-mm-diam dots. As shown in Fig. 1, a δ-doped (Be) sheet was inserted after the buffer layer in order to remove the Schottky barrier bandbending and flatten out all the band profiles.

Single barriers of AlGaInAs and AlGaAs were inserted into the GaAs so that the potential barrier would prevent electrons from reaching the collector contact until the highest potential was overcome. The heterojunction barriers were placed close enough to the surface so that the carriers would

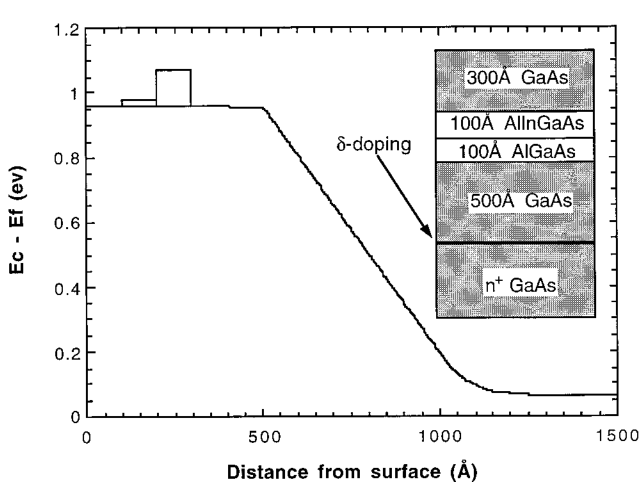

FIG. 1. Band profile and sample structure of the sample designed to measure the conduction-band offset between AlInGaAs and AlGaAs. Replacement of the AlGaAs layer allows for the measurement of ΔE_c between GaAs and AlGaInAs. From there, ΔE_c between the quaternary and AlGaAs can be deduced.

[a)]Present address: Division of Engineering and Applied Sciences, Harvard University, Cambridge Mass. 02138. Electronic mail: venky@deas.harvard.edu

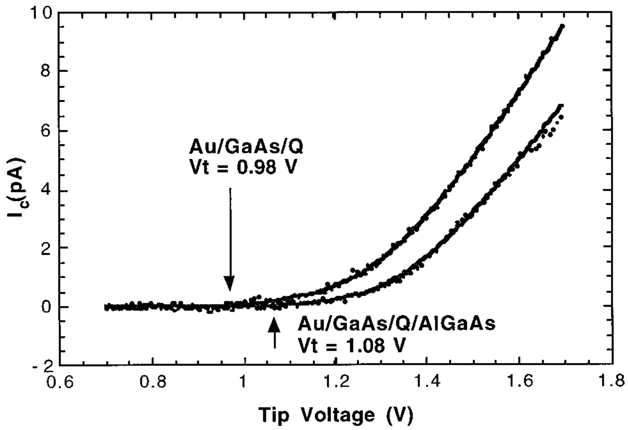

FIG. 2. BEES spectra comparison between AlGaInAs and AlGaAs. The difference between the thresholds correspond to the conduction-band offset at the AlGaInAs/AlGaAs heterointerface.

still be traveling ballistically upon reaching them. Through extensive study, the Au/GaAs SB has been shown to give uniform, reproducible results. Therefore, any change in the BEEM spectra can be directly attributed to heterojunction barriers underneath the surface.

In order to obtain the ΔE_c, we measured ballistic electron emission spectroscopy (BEES) spectra for a series of three samples. The first one is a sample containing only GaAs and the δ-doped layer, which gave a BEES threshold of 0.96 ± 0.03 V. The second sample, which has a 100 Å quaternary layer, AlGaInAs, below the cap resulted in an average BEEM threshold of 0.98 ± 0.04. This value is slightly higher than that of the reference sample, but it still falls within the error of the BEES measurement. For the third sample, an additional 100 Å layer of $Al_{0.2}Ga_{0.8}As$ (AL2) was placed *behind* the quaternary layer so that the Q/AL2 offset could be measured (Fig. 1). BEES gave a threshold of 1.08 ± 0.04 eV of this sample. Comparison of this value with that of sample 2 gives a conduction-band offset at the AlGaInAs/AlGaAs heterojunction of 100 ± 40 meV. Spectra displaying this comparison can be seen in Fig. 2 and all results are listed in Table I.

Under standard operating conditions, the laser structure goes under a 10 s, 900 °C anneal. To know the Q/AL2 offset under working conditions, the Q and AL2 samples were measured after the annealing procedure was performed. The

TABLE I. BEES results for the samples used to measure ΔE_c. From this data, the AlGaInAs/AlGaAs offset was found to be 100 ± 40 meV.

Sample (all Au capped)	BEES threshold (V)	Annealed V_t (V)
GaAs	0.96 ± 0.02	
GaAs/AlGaInAs	0.98 ± 0.04	0.97 ± 0.02
GasAs/AlGaInAs/AlGaAs	1.08 ± 0.04	1.01 ± 0.03
GaAs/AlGaAs	1.14 ± 0.03	

BEES thresholds for both samples decreased after the anneal, and the offset between Q and AL2 was also found to decrease from 100 to 40 meV. This result is attributed to the diffusion of In into the AlGaAs. These results are in agreement with secondary ion mass spectroscopy measurements,[10] which showed the In diffusion.

A final sample with only $Al_{0.2}Ga_{0.8}As$ was also grown under the same conditions as a test for transitivity. If transitivity holds, a value of 1.08 eV $(0.96+0.02+0.1$ eV) would be expected as the BEES threshold for this sample. However, measurements on this sample gave a value of 1.14 ± 0.04 eV, 60 meV higher than the expected sum, but in direct agreement with the previously reported BEES threshold.[7] It has been known that variations in interfacial layers, arising from growth,[11] doping,[12] or interdiffusion[13] have pronounced effects on the electrical properties in semiconductors. The nonideality can indeed be responsible for slight changes in the measured band offset values. As the final obtained value is strongly dependent on multiple samples and multiple grown interfaces, variations from the transitivity rule should be expected.

In conclusion, we have used BEES to measure the conduction-band offset between the strained VCL quantum well, AlGaInAs, and its barrier, AlGaAs. The three-sample technique employed gave a ~100 meV offset between the AlGaInAs quantum well and the AlGaAs layer. Under a high-temperature anneal, this value was found to decrease to ~40 meV confirming In diffusion from the QW layer to the ternary barrier.

The authors would like to acknowledge Air Force Office of Scientific Research Grant Nos. 442530-2537 and 442530-25364. This work was also funded under a CULAR grant through Los Alamos National Laboratory.

[1] R. G. Waters, R. J. Dalby, J. A. Baumann, and A. H. Shepard, IEEE Photonics Technol. Lett. **3**, 409 (1991).
[2] S. Corzine and L. A. Coldren, Proceedings of the Society of Photo-Optical Instrumentation Engineering (SPIE), 1993, Vol. 1850, p. 177.
[3] J. Ko, C.-H. Chen, and L. A. Coldren, Electron. Lett. **32**, 2099 (1996).
[4] J. Ko, E. R. Hegblom, Y. Akulova, B. J. Thibeault, and L. A. Coldren, Conference on Lasers and Electron-Optics (CLEO) of IEEE and OSA (Tech. Digest), 1997, Vol. 11, p. 289.
[5] W. J. Kaiser and L. D. Bell, Phys. Rev. Lett. **60**, 1406 (1988); L. D. Bell and W. J. Kaiser, *ibid.* **61**, 2368 (1988).
[6] For a recent review of BEEM, see M. Prietsch, Phys. Rep. **253**, 163 (1995).
[7] J. J. O'Shea, E. G. Brazel, M. E. Rubin, S. Bhargava, M. A. Chin, and V. Narayanamurti, Phys. Rev. B **56**, 2026 (1997).
[8] S. Bhargava, H.-R. Blank, V. Narayanamurti, and H. Kroemer, Appl. Phys. Lett. **70**, 759 (1997).
[9] H. Palm, M. Arbes, and M. Schulz, Phys. Rev. Lett. **71**, 2224 (1993).
[10] J. Ko, Ph.D. thesis, University of California, Santa Barbara (1998).
[11] M. Cantile, L. Sorba, P. Faraci, S. Yildirim, G. Bratina, A. Franciosi, T. J. Miller, M. I. Nathan, and L. Tapfer, J. Vac. Sci. Technol. B **12**, 2653 (1994).
[12] S. P. Watkins, H. D. Cheung, G. Knight, and G. Kelly, Appl. Phys. Lett. **68**, 1960 (1996).
[13] G. Theodorou and C. Tserbak, Phys. Rev. B **51**, 4723 (1995).