Multiple wavelength anisotropically polarized mid-infrared emission from InAs quantum dots

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(Received 14 December 2005; accepted 26 March 2006; published online 12 May 2006)

Multiple wavelength, anisotropically polarized midinfrared electroluminescence from self-assembled InAs quantum dots grown in AlGaAs/GaAs heterostructures has been observed at 77 K. Electrons are injected into excited quantum dot states using a graded AlGaAs injector. Direct tunneling out of the quantum dot excited states is prevented by means of a superlattice electron filter. Two midinfrared peaks are seen in the electrically pumped surface emission spectra of the device. The emission peaks are orthogonally polarized within the growth plane, indicating photon emission from intersublevel electron transitions within anisotropically shaped quantum dots. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2202824]

The formation of InAs quantum dots (QDs) by means of the Stranski-Krastanow self-assembled growth process[1] has become a standard method for fabricating semiconductor nanostructures using molecular-beam epitaxy (MBE). The three-dimensional (3D) confinement offered by these dots results in a delta-function density of states for carriers within them.[2,3] This unique electronic structure has served as the motivation for the fabrication of efficient interband emitters[4,5] utilizing quantum dots, and operating in the near-infrared portion of the optical spectrum.

There is also significant interest in the midinfrared (mid-IR) optical properties of self-assembled InAs QDs. Much of this interest has been spurred by the potential application of QD devices for mid-IR light detection.[6,7] With this goal in mind, studies of intersublevel optical transitions in QDs have mostly focused on absorption[8–10] or photoconductivity[11,12] measurements. However, the same transitions which allow for the fabrication of mid-IR QD photodetectors are the fundamental transitions necessary for the development of QD mid-IR emitters. Recently, several works have shown mid-IR electroluminescence (EL) from interband quantum dot lasers[13,14] and quantum dots embedded in cascade structures.[15–17] The ultimate goal of such work is to build on current quantum cascade technology in order to develop a low-threshold current density, surface-emitting mid-IR laser utilizing quantum dots. While intersublevel absorption measurements are useful as aids in the design of such devices, additional, important information for the development of mid-IR QD sources can be gleaned from the study of QD intersublevel emission. Luminescence studies of mid-IR emission spectra do not require rigorous control of dot doping density, nor do they suffer from the difficulties associated with signals from free-carrier absorption which complicate QD absorption measurements in the mid-IR. On its own, the study of mid-IR emission from quantum dot cascade structures can serve as a valuable tool for understanding intersublevel transitions in QDs and for the future development of a QD mid-IR laser.

The structures we have investigated were grown by molecular-beam epitaxy in a Varian Gen II system, on an $n+(100)$ oriented GaAs substrate. The device consists of an injector region, the QD active region, and a superlattice filter to extract the electrons from the QDs. The sample is capped by a highly doped n-GaAs layer for contact formation. The injector uses an n-doped $Al_xGa_{(1-x)}As$ ramp from $x=0$ to $x=0.2$ followed by 500 Å of undoped $Al_{0.2}Ga_{0.8}As$ and a thin AlAs tunnel barrier, upon which is grown the layer of InAs QDs. A $GaAs/Al_{0.33}Ga_{0.67}As$ superlattice (SL) consisting of six periods of 79 Å GaAs wells and 11 Å AlGaAs barriers follows the dot layer and acts as an electron energy filter. Figure 1 shows the sample structure, including the superlattice states and estimated dot states, under a 20 kV/cm bias.

The superlattice minibands shaded in Fig. 1 are tailored to block transmission through the dot at the injector energy while promoting electron escape from the dot at lower-

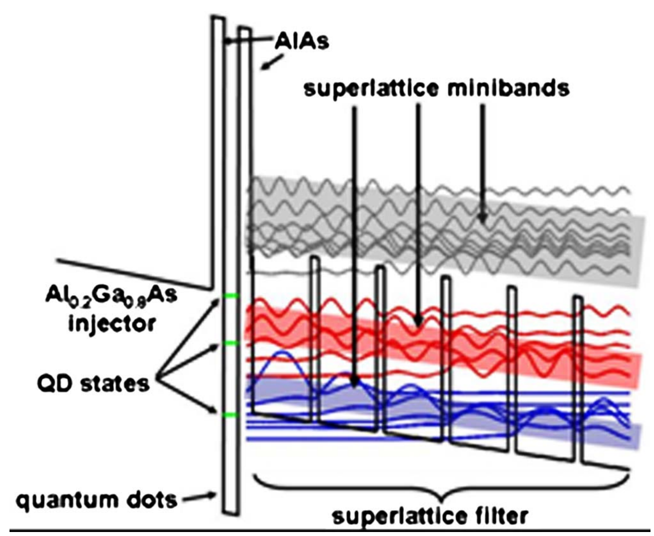

FIG. 1. (Color online) Conduction-band structure for a multiple wavelength mid-IR emitter at 20 kV/cm bias. The quantum dot layer is depicted schematically as a narrow quantum well. States in the superlattice are shown by their modulus squared, and the extraction minibands are shaded to aid in viewing.

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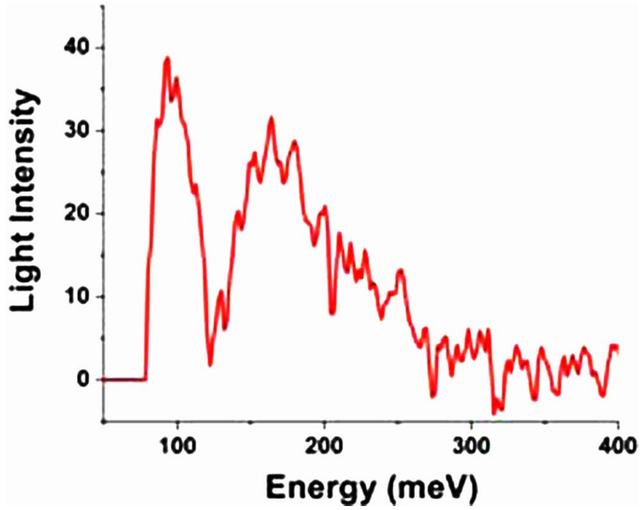

FIG. 2. (Color online) Electroluminescence spectrum for a multiple wavelength mid-IR QD emitter. The sample was operated in pulsed mode (20 kHz, 20 μs pulse width) at a voltage corresponding to an electric field of 20 kV/cm across the active region. Two distinct emission peaks can be seen at about 100 and 175 meV.

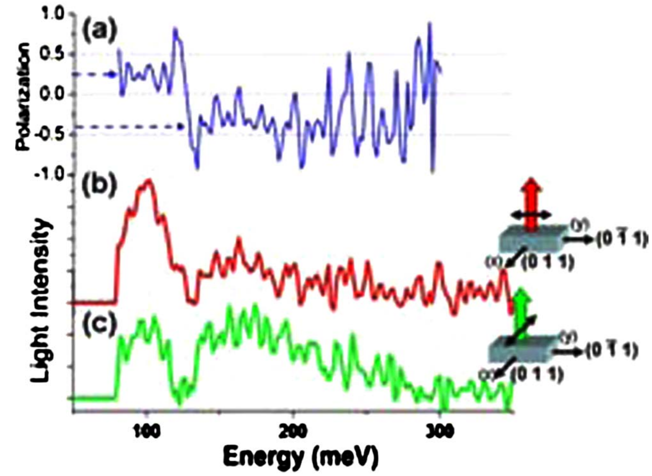

FIG. 3. (Color online) (a) Plot of the degree of polarization of the surface emission as a function of energy for light emitted from QD device. Despite the noisy signal, one can see a clear preferred polarization for each of the two emission peaks. A polarization of 1 corresponds to light polarized entirely in the $[0\bar{1}1]$ direction while a polarization of -1 corresponds to light polarized entirely in the $[011]$ direction; (b) and (c) show the QD emission spectra for $[0\bar{1}1]$ and $[011]$ polarized emission, respectively.

energy levels. Despite this design, electron injection above, but near the higher-energy miniband does suggest the possibility of some carrier escape from excited QD states before an intersublevel transition can occur. Such a loss of carriers by means of direct tunneling through higher-energy states in the filter would weaken the mid-IR emission signal. However, the high-energy injection and the filter design are intended to allow for the probing of transitions from excited energy states in the QDs that would not be accessible with a lower-energy injector.

Extraction of carriers from the QD ground state would be most efficient if this lowest dot state aligned with the lower-energy miniband of the superlattice filter. Interband photoluminescence studies of comparable dots grown on thin AlAs and embedded in $Al_{0.2}Ga_{0.8}As$ suggest that the QD ground state for our sample is located slightly below the GaAs band edge, about 50 meV or so below the SL miniband. While this decreases the efficiency of carrier extraction from the dot ground state, it does allow for mid-IR emission of light at energies greater than the emission energy of previous devices.[15] Provided that carriers can still escape the dot by other means, such as thermal excitation or tunneling, light can be extracted from the device. While neither of the two above mechanisms are likely to allow for population inversion, they are sufficiently strong enough to allow probing of intersublevel transitions in our quantum dot layer via electroluminescence.

Samples were fabricated using evaporated and annealed concentric ring Pd/Ge contacts on mesa structures. Samples were mounted on copper heatsink blocks and surface emission was studied at 77 K with a Nicolet 8700 Fourier transform infrared (FTIR) spectrometer using a lock-in step-scan technique. The samples were pulsed with current densities from 2 to 10 A/cm^2 at 20 kHz with 20 μs pulse widths. As observed in previous studies,[15] emission intensity saturated at low current densities (5 A/cm^2) and the spectral shape did not change as a function of current density.

Figure 2 shows the surface emission spectrum from the QD sample. Two separate peaks are clearly seen; a narrower peak at 100 meV and a broader emission peak at about 175 meV. The dual peaks suggest the emission of light from two separate intersublevel transitions within the quantum dots. The presence of the higher-energy peak confirms the presence of QD conduction-band ground states near the GaAs band edge.

Previous studies of similar samples determined the mid-IR EL signal to be a result of intersublevel transitions within the QDs, as opposed to transitions in the SL or current heating.[15] However, to further understand the nature of the multipeak spectrum seen from the QD sample, the polarization of the EL signal is studied. A distinct polarization is seen in the sample's mid-IR surface emission spectrum. The strength of the higher energy signal is found to be maximized for light emission polarized in the $[011]$ direction, while the lower-energy peak intensity is maximized in the $[0\bar{1}1]$ polarization direction. Figure 3 shows the emission spectra for light polarized in the $[0\bar{1}1]$ direction [Fig. 3(b)] and in the $[011]$ direction [Fig. 3(c)] (henceforth referred to as the **y** and **x** directions, respectively). The higher-energy peak is quite strongly polarized in the **x** direction and almost disappears when the orthogonal **y** polarization is analyzed. While the lower-energy peak is not polarized to the same extent, its emission is decidedly stronger for spectra polarized in the **y** direction. To better illustrate polarization effects, Fig. 3(a) shows the degree of polarization of the emitted light from the sample as a function of emission energy as given by $P=(I_y-I_x)/(I_x+I_y)$. By viewing the data in this manner, one can distinctly see two regimes of polarization corresponding to the device's two orthogonally polarized emission peaks.

The polarization of the surface emitted light allows added insight into the nature of the optical transitions in the sample, further reinforcing our QDs as the origin of this signal. Most importantly, we can assert that light emission, to the extent that it is polarized, is neither a result of current heating or scattered light from superlattice transitions, as these mechanisms would not produce light preferentially polarized in either direction of the sample's growth plane. Ad-

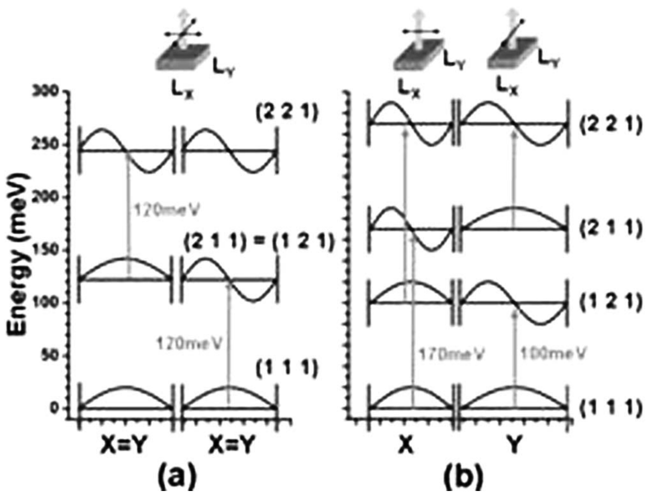

FIG. 4. (a) Schematic of x and y energy states for simple 3D parallelepiped structure where $L_x = L_y \neq L_z$. As the wave functions for such a quantum structure can be approximated as separable, each eigenstate can be defined by three quantum numbers (n_x, n_y, n_z). Because states (2 1 1) and (1 2 1) are degenerate, no net polarization preference would be seen for transitions between excited states and the ground state (1 1 1). However, in (b), $L_x \neq L_y$, which splits the degeneracy for the (1 2 1) and (2 1 1) states, such that the lower-energy transition is polarized in the direction of the parallelepiped's elongated dimension (**y**), while the higher-energy transition is polarized in the orthogonal (**x**) direction.

ditionally, these results suggest an anisotropy in QD shape in the growth plane.

To better understand the polarized emission peaks one can use the simplest model of a quantum dot as an InAs quantum box with AlAs potential barriers, the electron states of which are shown in Fig. 4. While undoubtedly a simplified approximation of an actual QD, such a model allows a qualitative understanding of the effect of QD shape on intersublevel transitions within the dot. For a dot modeled as a parallelepiped with $L_x = L_y = L$ and $L_z = L/5$, the first excited states of the structure are degenerate, and an equal number of photons emitted by optical transitions from this state to the ground state will be polarized in the x and y directions. However, for a structure where L_y and L_x are increased and decreased by, for instance, 15%, respectively, the excited states are no longer degenerate. An elongation of the QDs along the **y** direction brings the **y** polarized optical transitions to lower energies than the equivalent transitions polarized along the **x** direction.

Such an elongation of InAs QDs in the $[0\bar{1}1]$ direction has been observed through *in situ* studies of InAs growth on AlAs surfaces.[18] Polarization-dependent photoconductivity for surface incident mid-IR radiation has also been seen in QDs (and attributed to asymmetric QD shape), for InAs QDs grown on InAlAs lattice matched to InP.[19] However, to our knowledge, this is the first example of polarized light emission in a mid-IR EL spectrum from QDs.

In conclusion, we have observed mid-IR emission at multiple wavelengths from InAs quantum dots embedded in an AlGaAs/AlAs/GaAs heterostructure. The emission peaks are orthogonally polarized in the growth plane of the sample, suggesting an anisotropy in the shape of the InAs quantum dots grown on the thin AlAs tunneling barrier. As the sample structure used differs from that of previous work[15] only in the injector design, it is apparent that the design of the surrounding heterostructure can significantly influence mid-IR QD emission. Additionally, this work adds to the understanding of energy states in quantum dots and their relation to the morphology of the dots. Thus, not only do these results present the possibility of controlling mid-IR QD emission via the surrounding matrix, they also suggest the possibility of an extended wavelength range for future quantum dot mid-IR emitters and lasers.

This work was supported in part by the U.S. Army Research Office under Grant No. DAAG55-98-1-0270. One of the authors (D.W.) would like to thank the Princeton Council on Science and Technology for additional funding. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

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