Room-temperature far-infrared emission from a self-organized InGaAs/GaAs quantum-dot laser

Sanjay Krishna, Omar Qasaimeh, and Pallab Bhattacharya[a)]
Solid State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122

Patrick J. McCann and Khosrow Namjou
Laboratory for Electronic Properties of Materials, School of Electrical and Computer Engineering, University of Oklahoma, Norman, Oklahoma 73019-1023

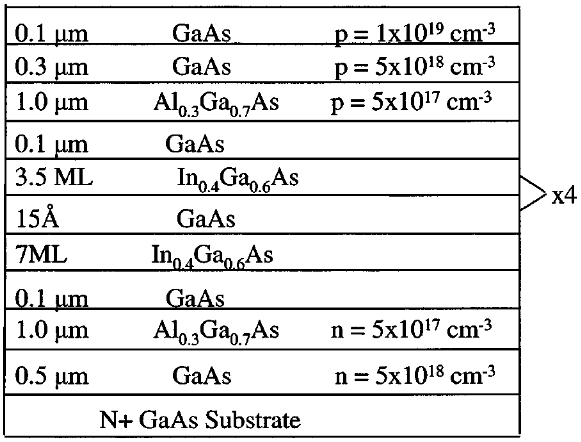
(Received 2 February 2000; accepted for publication 12 April 2000)

Far-infrared spontaneous emission at 300 K and lower temperatures, due to intersubband transitions in self-organized $In_{0.4}Ga_{0.6}As$/GaAs quantum dots, has been characterized. Measurements were made with a multidot layer near-infrared ($\sim$1 μm) interband laser. The far-infrared signal, centered at 12 μm, was enhanced after the interband transition reached threshold at 300 K. The results are explained in terms of the carrier dynamics in the dots. © *2000 American Institute of Physics.* [S0003-6951(00)04923-8]

There is an increasing demand for sources in the far infrared (8–20 μm) for applications such as optical IR spectroscopy, point-to-point atmospheric communication and optical radars. Far-infrared (FIR) sources are also needed for monitoring of chemical species and pollutants and for remote control and sensing. Early reports on light-emitting diodes[1–3] were followed by the quantum-cascade laser,[4–6] a unipolar semiconductor laser based on intersubband transitions in quantum wells. FIR emission has also been reported in quasi-one-dimensional wires grown by molecular-beam epitaxy (MBE).[7] Recently, room-temperature photoluminescence has been reported in the 3–4 μm range using PbSe/PbSrSe multiple-quantum-well structures.[8] Self-organized quantum dots (QDS) are expected to display FIR emission and absorption characteristics as the energy spacing of the bound states in these dots lies in the FIR regime. Quantum-dot infrared photodetectors (QDIP) based on intersubband and subband-to-continuum transitions have already been reported by us and other groups.[9–11] However, there have been very few reports on FIR emission from the dots. Vorob'ev *et al.*[12] have reported the observation of weak FIR emissions from interband InGaAs/GaAs quantum-well and InGaAs/AlGaAs quantum-dot lasers. In this letter, we report the spectral characteristics of FIR spontaneous emission from self-organized InGaAs/GaAs interband quantum-dot lasers.

The electron energy-level spacing between the ground state and the first-excited state and the ground state and the GaAs conduction-band edge in $In_{0.4}Ga_{0.6}As$/GaAs self-organized quantum dots, as determined from theory[13] and experiments,[14] are about 60–80 and 230–250 meV, respectively. However, in order to observe radiative transitions from these states, we must have favorable carrier populations and relaxation times. From analysis of the small-signal modulation of quantum-dot interband lasers, we have estimated long (30–50 ps) electron relaxation times from the continuum to the ground state at room temperature.[15] Since the capture time from the continuum to the confined states is only a few picoseconds,[16,17] the intersubband relaxation time can be estimated to be about 30–50 ps. This is supported by direct spectroscopic measurements reported recently.[18] These favorable relaxation times invoke the possibility of intersubband lasing in quantum dots.[19]

The experiments reported here were performed on multidot layer single-mode ridge waveguide interband lasers ($\lambda \sim 1$ μm) grown by molecular-beam epitaxy. The heterostructure is depicted in Fig. 1. To choose the amount of charge for the first and the second layers of dots, the reflection high-energy electron diffraction pattern was monitored to determine when the streaky pattern turned to a spotty one. The first layer of dots formed after 7 ML of $In_{0.4}Ga_{0.6}As$ whereas the following layers of dots, separated by a 15 Å GaAs spacer, formed after 3 ML of $In_{0.4}Ga_{0.6}As$ charge. The subsequent layers of dots have been found to form more rapidly because of the strain-driven self-alignment and vertical coupling in the growth direction, which defines points of extremal strain on the growth front.[20] The growth conditions are described elsewhere in detail.[21] Cross-sectional transmission electron microscopy and atomic-force microscopy reveal the dots to have a base length of 20 nm and



0.1 μm	GaAs	$p = 1x10^{19}$ cm^{-3}	
0.3 μm	GaAs	$p = 5x10^{18}$ cm^{-3}	
1.0 μm	$Al_{0.3}Ga_{0.7}As$	$p = 5x10^{17}$ cm^{-3}	
0.1 μm	GaAs		
3.5 ML	$In_{0.4}Ga_{0.6}As$		x4
15Å	GaAs		
7ML	$In_{0.4}Ga_{0.6}As$		
0.1 μm	GaAs		
1.0 μm	$Al_{0.3}Ga_{0.7}As$	$n = 5x10^{17}$ cm^{-3}	
0.5 μm	GaAs	$n = 5x10^{18}$ cm^{-3}	
N+ GaAs Substrate			

FIG. 1. Schematic of the five-layer $In_{0.4}Ga_{0.6}As$/GaAs quantum-dot laser heterostructure grown by solid-source molecular-beam epitaxy (MBE).

[a)]Electronic mail: pkb@eecs.umich.edu

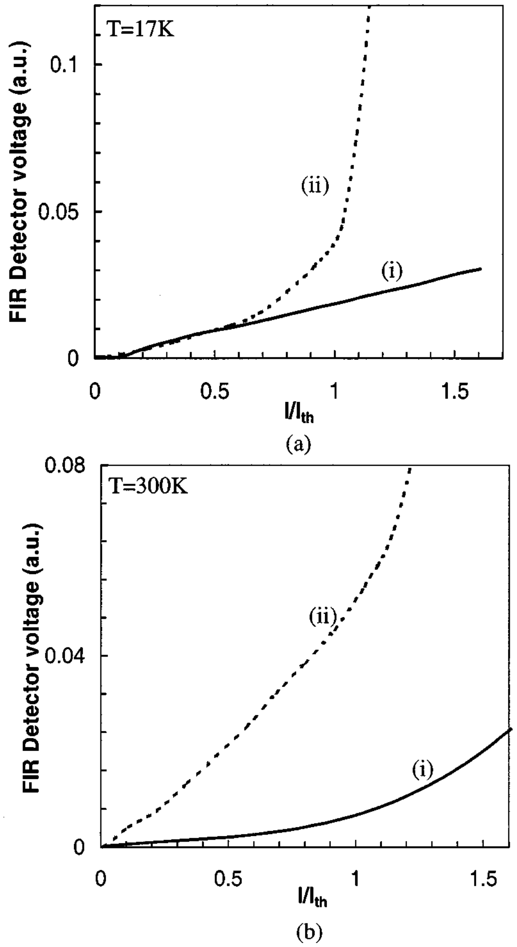


FIG. 2. Spontaneous emission as a function of injected current (a) at $T=17\,\mathrm{K}$: (i) using a bandpass filter centered at 12.8 μm with a stop band of 2 μm on either side; (b) at $T=300\,\mathrm{K}$: (i) spontaneous response using the bandpass filter centered at 12.8 μm. The dashed line, (ii), depicts the interband lasing signal.

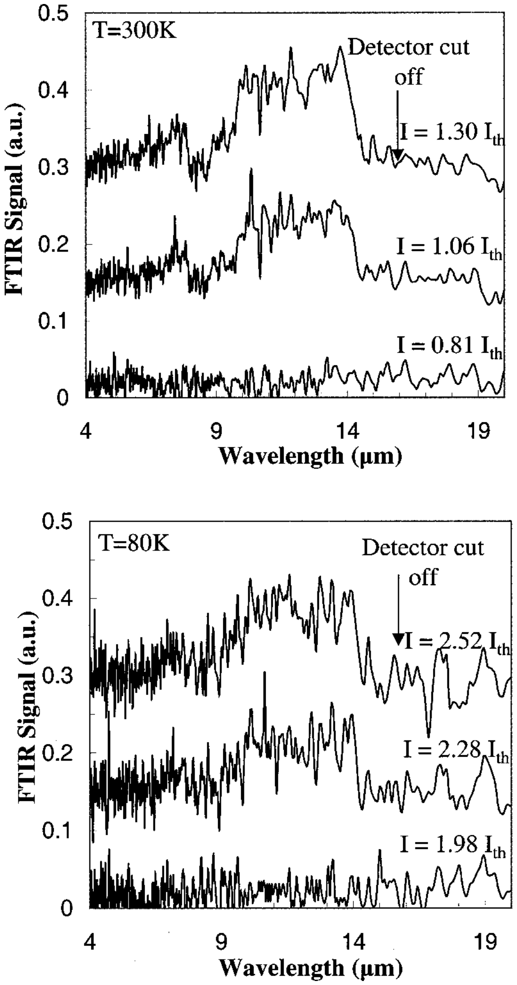


FIG. 3. Enhanced spontaneous emission measured using a Fourier transform infrared spectrometer for different injection levels at (a) $T=300$ K and (b) $T=80$ K.

height of 7 nm with a density of $5\times10^{10}\,\mathrm{cm}^{-2}$. Lasers were fabricated using standard photolithography, lift-off techniques, and a combination of dry and wet etching. The width of the waveguide is 3 μm and the length of the laser varied from 400 to 600 μm. *p*- and *n*-type metallization were done using Pd/Zn/Pd/Au and Ni/Ge/Au/Ti/Au, respectively. Electroluminescence was measured by mounting the QD laser in a closed-cycle helium cryostat. Electrical injection was performed with a HP8114 pulse generator and the trigger signal from the generator was used for lock-in amplification. The output light was directed through a bandpass filter. The light was then coupled to an EG&G Judson liquid-nitrogen-cooled HgCdTe detector (J-15-D26), which could detect radiation from 5–26 μm. Bandpass filters were used to select the FIR output.

Figure 2 depicts the FIR signal amplitude as a function of injection current at $T=17$ and 300 K. The dashed lines indicate the 1 μm interband lasing characteristics ($I_{\mathrm{th}}=260\,\mathrm{mA}$). The threshold current was much higher than that observed in lasers made out of the same material without contact pads ($I_{\mathrm{th}}=30\,\mathrm{mA}$). The high series contact resistance, due to the fabrication process, could be responsible for this large threshold current. Since the threshold current was so high, care was taken to couple the device very well to the heat sink and to stabilize the temperature at all values of injected current. The solid lines represent the response of the laser when a filter centered at 12.8 μm with a pass band of 2 μm on either side was placed at the output of the laser. The bandpass filter has a very sharp roll-off and the transmission outside the band is less than 0.1%. A distinct enhancement in the slope of the emission is observed in the data recorded at 300 K, when the interband threshold is reached. This is to be expected, as the ground state of the dots is depleted of carriers at a much faster rate due to stimulated emission once threshold is reached [the stimulated emission time (τ_{stim}) is much smaller than the spontaneous emission time (τ_{sp})].

Spectral measurements of the FIR output were performed on the quantum-dot lasers at $T=80\,\mathrm{K}$ and $T=300\,\mathrm{K}$. The lasers were wire bonded and mounted in a cold-finger cryostat with a ZnSe window and were biased with a low-frequency positive pulse ($f=10\,\mathrm{Hz}$, duty cycle $=25\%$). The temperature of the device was stabilized by using a Lakeshore temperature controller. A silicon filter was used to block the interband signal at 1 μm. Far-infrared emission was measured as a function of the injection bias using an Oriel MIR 8000 Fourier transform infrared (FTIR) spectrometer. An EG&G Judson liquid-nitrogen-cooled HgCdTe detector (J-15-D12) was used to detect the FIR signal. The recorded data were corrected for the ambient blackbody background response of the system and are depicted in

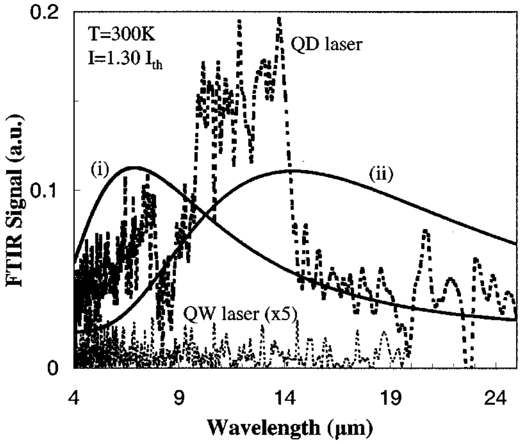


FIG. 4. Radiation from a blackbody source at (i) $T=420\,\mathrm{K}$ and (ii) $T=200\,\mathrm{K}$, corresponding to heat sink temperatures of 300 and 80 K, respectively. The dotted lines represent the room-temperature FIR emission from the interband quantum-dot laser. Also shown is the FIR response from a similar interband laser containing multiple-quantum-well layers.

Fig. 3. At $T=300\,\mathrm{K}$, no emission was observed when the laser was biased below threshold. However, as the threshold bias was reached, a broad peak, centered around 12 μm, was observed. This peak increased in amplitude until about $I=1.2\,I_{\mathrm{th}}$ and then remained almost constant in magnitude [Fig. 3(a)]. We believe this peak is due to radiative transitions between the excited and the ground states in the dots. The observed emission could be due to transitions from the higher excited states in the dots since the emission energy (100 meV, 12 μm) is higher than the energy spacing between the first-excited state and the ground state of the dot (60–80 meV). However, transitions at lower energies could not be observed as the detector had a cutoff at 16 μm (~80 meV). When the laser is biased above threshold, the electrons in the ground state of the dots are depleted at the stimulated emission rate ($\tau_{\mathrm{stim}}\sim 5-10\,\mathrm{ps}$) by interband photons, leading to a more nonequilibrium intersubband population. Similar emission centered at 12 μm was also observed at $T=80\,\mathrm{K}$ [Fig. 3(b)]. However, at this ambient temperature, the laser had to be biased well above interband threshold to observe the FIR emission. This could be due to the fact that the intersubband electron relaxation rate is much faster ($\tau\sim 5-6$ ps) (Ref. 18) at lower temperatures. Therefore, a nonequilibrium population between the states is harder to achieve and maintain when the ground-state population is depleted at approximately the same rate by interband lasing. It is important to mention that carrier relaxation in quantum dots is largely controlled by electron–hole scattering, an Auger-like process, whose rate decreases with increase of temperature.[15,18]

To confirm that the observed peaks were not due to thermal heating of the device, we analyzed the data by considering emission from a blackbody source. Local temperatures at the laser mirrors have been measured in GaAs-based quantum-well lasers using micro-Raman spectroscopy[22] and found to be about 120 °C higher than the temperature of the heat sink. Using a value of $\Delta T=120\,^{\circ}\mathrm{C}$, the temperature in our laser mirrors can be estimated to be about 420 and 200 K when the heat sink is at 300 and 80 K, respectively. The blackbody curves corresponding to these two temperatures are shown in Fig. 4 along with the observed room-temperature spontaneous emission from the interband QD laser. There is a large difference in the blackbody response between the two curves around 12 μm, where the FIR emission is observed. This suggests that the emission is not due to blackbody radiation from the device. To further confirm that the FIR emission was from the quantum dots, the long-wavelength emission of a similar laser containing multiple-quantum wells with interband emission at 1.53 μm was measured. There was no FIR emission from this device, as is shown in Fig. 4.

In conclusion, we report the characteristics of room-temperature spontaneous FIR emission in self-organized $\mathrm{In_{0.4}Ga_{0.6}As/GaAs}$ quantum dots, possibly resulting from intersubband transitions. Measurements were made with electroluminescent interband lasers at 300 K and lower temperatures and the results are explained on the basis of favorable intersubband electron relaxation rates. The temperature variation of the emission suggests that the radiation is not due to blackbody heating of the device.

The authors would like to thank O. Alkhouli for helping them with the FTIR measurements. This work is supported by the National Science Foundation under Grant No. ECS9820129.

[1] M. Helm, P. England, E. Colas, F. DeRosa, and S. J. Allen, Jr., Phys. Rev. Lett. **63**, 74 (1989).
[2] S. Sauvage, Z. Moussa, P. Boucaud, and F. H. Julien, Appl. Phys. Lett. **70**, 1345 (1997).
[3] C. Sirtori, F. Capasso, J. Faist, D. L. Sivco, A. L. Hutchinson, and A. Y. Cho, Appl. Phys. Lett. **66**, 4 (1995).
[4] J. Faist, F. Capasso, D. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, Science **264**, 553 (1994).
[5] J. Faist, F. Capasso, D. L. Sivco, A. L. Hutchinson, C. Sirtori, and A. Y. Cho, Infrared Phys. Technol. **36**, 99 (1995).
[6] J. Faist, F. Capasso, C. Sirtori, D. Sivco, A. L. Hutchinson, S-N. G. Chu, and A. Y. Cho, Appl. Phys. Lett. **64**, 1144 (1994).
[7] M. Grayson, D. C. Tsui, M. Shayegan, K. Hirakawa, R. A. Ghanbari, and H. I. Smith, Appl. Phys. Lett. **67**, 1564 (1995).
[8] P. J. McCann, K. Namjou, and X. M. Fang, Appl. Phys. Lett. **75**, 3608 (1999).
[9] J. Phillips, P. Bhattacharya, S. W. Kennerly, D. W. Beekman, and M. Dutta, IEEE J. Quantum Electron. **35**, 936 (1999).
[10] S. Maimon, E. Finkman, G. Bahir, S. E. Schacham, J. M. Garcia, and P. M. Petroff, Appl. Phys. Lett. **73**, 2003 (1998).
[11] D. Pan, E. Towe, and S. Kennerly, Appl. Phys. Lett. **73**, 1937 (1998).
[12] L. E. Voro'bev, D. A. Firsov, V. A. Shalygin, V. N. Tulupenko, Yu. M. Shemyakov, N. N. Ledentsov, V. M. Ustinov, and Zh. I. Alferov, JETP Lett. **67**, 275 (1998).
[13] H. Jiang and J. Singh, Phys. Rev. B **56**, 4696 (1996).
[14] K. Kamath, N. Chervala, K. K. Linder, T. Sosnowski, H.-T. Jiang, T. Norris, J. Singh, and P. Bhattacharya, Appl. Phys. Lett. **71**, 927 (1997).
[15] D. Klotzkin, K. Kamath, and P. Bhattacharya, IEEE Photonics Technol. Lett. **9**, 1301 (1997).
[16] R. Heitz, M. Veit, N. N. Ledenstov, A. Hoffmann, D. Bimberg, V. M. Ustinov, P. S. Ko'pev, and Zh. I. Alferov, Phys. Rev. B **56**, 10435 (1997).
[17] D. Morris, N. Perret, and S. Fafard, Appl. Phys. Lett. **75**, 3593 (1999).
[18] T. Sosnowski, T. Norris, H. Jiang, J. Singh, K. Kamath, and P. Bhattacharya, Phys. Rev. B **57**, R9423 (1998).
[19] J. Singh, IEEE Photonics Technol. Lett. **8**, 488 (1996).
[20] K. Kamath, N. Chervala, K. K. Linder, T. Sosnowski, H.-T. Jiang, T. Norris, J. Singh, and P. Bhattacharya, Appl. Phys. Lett. **71**, 927 (1997).
[21] K. Kamath, P. Bhattacharya, and J. Phillips, J. Cryst. Growth **175/176**, 720 (1997).
[22] G. Abstreiter, Appl. Surf. Sci. **50**, 73 (1991).