Lasing characteristics of InAs quantum dot lasers on InP substrate

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Abstract

Single-stack InAs self-assembled quantum dots (QD) lasers based on InP substrate have been grown by metalorganic vapor phase epitaxy. The narrow ridge waveguide lasers lased up to 260 K in continuous wave operation, and near room temperature in pulsed mode, with emission wavelengths between 1.59 to 1.74 μm. Above 200 K, a very low wavelength temperature sensitivity of 0.09 nm/K was obtained, which is as low as that caused by the refractive index change. Lasing spectra at different temperature revealed that the ground states and the excited states were almost overlapped, and formed a qusi-continuous band due to dot's large size and inhomogeneously broadening. These results will provide guidance for further development of long wavelength InAs QD lasers based on InP substrate.

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InAs quantum dot (QD) lasers based on InP substrate are of considerable interest as they offer the potential for telecommunication, as well as applications in long wavelength region of 1.8 to 2.3 μm, such as molecular spectroscopy, remote sensing of atmospheric and planetary gases and wind profile lidar. Room temperature operation of InAs quantum-dash lasers on (001) InP were demonstrated at wavelengths of about 1.60 μm[1] and recently up to 1.78 μm[2], however these quantum-dashes are basically one-dimensional quantum wire like structures. InAs QDs on InP substrates of emission wavelength up to 2 μm[3] and InAs QD lasing at 1.9 μm[4] were reported at low temperature of 77K. Recently, we discovered that the InAs QD size non-uniformity caused by alloy phase separation is one of the major reasons for low temperature performance of InAs QD lasers at long wavelength, improved dot size uniformity and luminescence efficiency have been achieved by inserting a thin GaAs interface layer between InAs QDs and the underlying InGaAs layer[5], which will enable room temperature operation of InAs QD lasers based on InP substrates.

The QD ensemble has energy bands instead of discrete energy levels due to inhomogeneously broadening, and the energy separation between bands has been engineered to obtain less temperature sensitive threshold[6]. However, on the other hand, when large InAs QDs are required at long emission wavelength, small energy separation even qusi-continuous states are expected. The effect of that on InAs QD lasers at long wavelength is still not well understood.

In this letter, we report lasing characteristics of single-stack InAs QD lasers based on InP substrate. The lasers lased up to 260 K in continuous wave (cw) operation, and near room temperature in pulsed mode, with emission wavelengths between 1.59 to 1.74 μm. Above 200 K, a very low wavelength temperature sensitivity of 0.09 nm/K was obtained, which is as low as that caused by the refractive index change. The experiments revealed that the ground states and the excited states were almost overlapped and formed a qusi-continuous band due to dot's large size and inhomogeneously broadening.

The InAs QD lasers were grown on (001) InP substrates using low-pressure metalorganic vapor phase epitaxy, which is believed to allow the formation of large dots, therefore longer wavelength. Trimethylindium (TMIn), triethylgallium, AsH_3 and PH_3 are used as precursors, and H_2 as carrier gas. Growth temperatures were in the range of 500 °C~550 °C for the InAs QD layers, and 650 °C for the rest of structures. The dots have an average lateral size around 60 nm and of 7 nm in height with area density of 3×10^{10} /cm^2. The laser structure consists a single-stack InAs QDs self-assembled on a thin GaAs interface layer within an tensile-strained InGaAs quantum well with thickness of 7 nm, which is further sandwiched between 150 nm InGaAsP (λg=1.35 μm) and 1.5 μm InP cladding layers on both sides, and finally a 200 nm InGaAs cap layer. A schematic drawing of band alignment is depicted in Figure 1. The insertion of a thin GaAs interface showed improvement in dot size distribution and luminescence efficiency[5], but also can minimize hot carrier effects through tunneling injection[7].

8-μm ridge waveguide lasers were fabricated from these structures with cavity lengths between 0.5 to 2.0 mm and no facet coating. The laser bars were affixed with indium, epilayer side up, onto a copper heat-sink and then mounted on the temperature-controlled cold finger of an optical cryostat. The optical output power was measured with a cooled InSb detector calibrated by a thermopile power meter when the average power was high. For most measurements, neutral density filters were used to avoid saturating the detector. The emission spectra were obtained by focusing the output optical beam onto the entrance slit of a 0.55-m monochrometer.

The lasers were operated in cw mode at heat-sink temperatures up to 260 K. Figure 2 shows the single facet light output characteristics versus current of a 1-mm-cavity-length laser at temperature of 80 K. Its threshold current and threshold current density were about 10 mA and 125 A/cm^2, respectively. The single facet output power exceeds 25 mW and the differential slope efficiency is about 27%. With increasing temperature, the slope efficiency did not change much until 160 K, then it became less that 8% between 180 and 260 K. In the inset of Fig. 2, the temperature behavior of the threshold current of the device is shown. Characteristic temperatures of T_0= 220 K were observed below 100 K which is reduced to 61 K to heat-sink temperature of 260 K. When the laser was operated under pulsed conditions (1μs, 1 kHz), it could operate at near room temperature of 280 K.

Cavity length plays an important role on lasing wavelength of QD lasers. The lasers of 2 mm cavity lased at wavelengths between 1.69 to 1.74 μm, and 1.59 to 1.69 μm for the lasers of 1 mm cavity. In Figure 3, cw lasing spectra of a 1-mm-cavity laser at different injection current are show at different temperatures. At 80 K, lasing started at wavelength of 1673 nm just above threshold, as current increases, typical QD broad emission spectra are observed. At 120 K, lasing also started near 1671 nm, but at injection of 30 mA two dominant longitudinal modes appeared at wavelengths of 1673 nm and 1635 nm, respectively, which is only 17 meV in energy separation; and increasing injection current resulted more emission modes in between. With further increasing temperature, at above 160 K, lasing only started and centered around 1625 nm, then at above 200 K, collective lasing was observed, and lasing spectra centered at 1635 nm are shown here at temperature of 260 K in Fig. 3. We believe that the observed two lasing modes at 1673 and 1635 nm represent a mode switching from a ground state to an excited state, but from different size sets of QDs. It's well known that at low temperature QD lasing spectra have unique features of many broadened longitudinal modes at high injection current[8], resulting from the presence of noninteracting dots, and collective lasing of the dot ensemble occurs only at elevated temperatures when homogeneous broadening becomes comparable or exceeds inhomogeneous broadening. Due to different dot sizes, the QD states form energy bands each having finite band width - inhomogeneous broadening, in the case of laser with 1 mm cavity, lasing modes at 1673 and 1635 nm correspond to transitions labeled 1, 2 in Fig. 1. In other words, lasing modes at 1673 and 1635 nm are recombination from ground states of small size dots and excited states of large dots, respectively. Therefore, it's not difficult to understand the difference of the energy separation of 17 meV observed here and 40 meV measured by room temperature photoluminescence. Even in this 17-meV-energy-separation, there exist more states including ground states of much smaller dots and excited states of much larger dots, which is evidenced by spectra only at high injection currents at 120 and 160 K in

Fig. 3, so a qusi-continuous band virtually formed in these long wavelength InAs QD laser structures.

For lasers with 2 mm cavity, mode switching behavior was not observed over the course of injection current and temperature. However, with increasing temperature, more longitudinal modes appeared at shorter wavelength side and diminished at longer wavelength side, resulting a noticeable blue shift for the overall lasing spectrum. This blue shift will partially compensate the red shift from the band gap shrinkage, and reduce the temperature sensitivity of the emission wavelength of QD lasers[9]. Figure 4 shows pulsed lasing spectra of a 2-mm-cavity laser. Temperature induced wavelength shift is as low as 0.09 nm/K, the same as that caused by the refractive index change[10].

In summary, we have presented lasing characteristics of InAs QD lasers based on InP substrate. These ridge waveguide lasers operated at temperature up to 260 K in cw mode, and near room temperature in pulsed mode, with emission wavelengths between 1.59 to 1.74 μm. Very low wavelength temperature sensitivity of 0.09 nm/K was obtained, which is as low as that caused by the refractive index change. It is shown that in long wavelength QD lasers the ground states and the excited states are almost overlapped and form a qusi-continuous band due to dot's large size and inhomogeneously broadening. The results will provide guidance for further development of long wavelength InAs QD lasers based on InP substrate.

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Figure Captions

Figure 1: A schematic drawing of band alignment of InAs QD laser structure. 1 and 2 represent transitions from ground state and excited state of different size sets of QDs.

Figure 2: Light output vs current of a 1-mm-cavity-length laser at temperature of 80 K. The inset shows the temperature dependence of the threshold current of the device.

Figure 3: cw lasing spectra of a 1-mm-cavity laser at different injection current measured at different temperatures.

Figure 4: Pulsed lasing spectra of a 2-mm-cavity laser, showing a very low wavelength temperature sensitivity of 0.09 nm/K.

Figure 1, Yueming Qiu, Applied Physics Letters

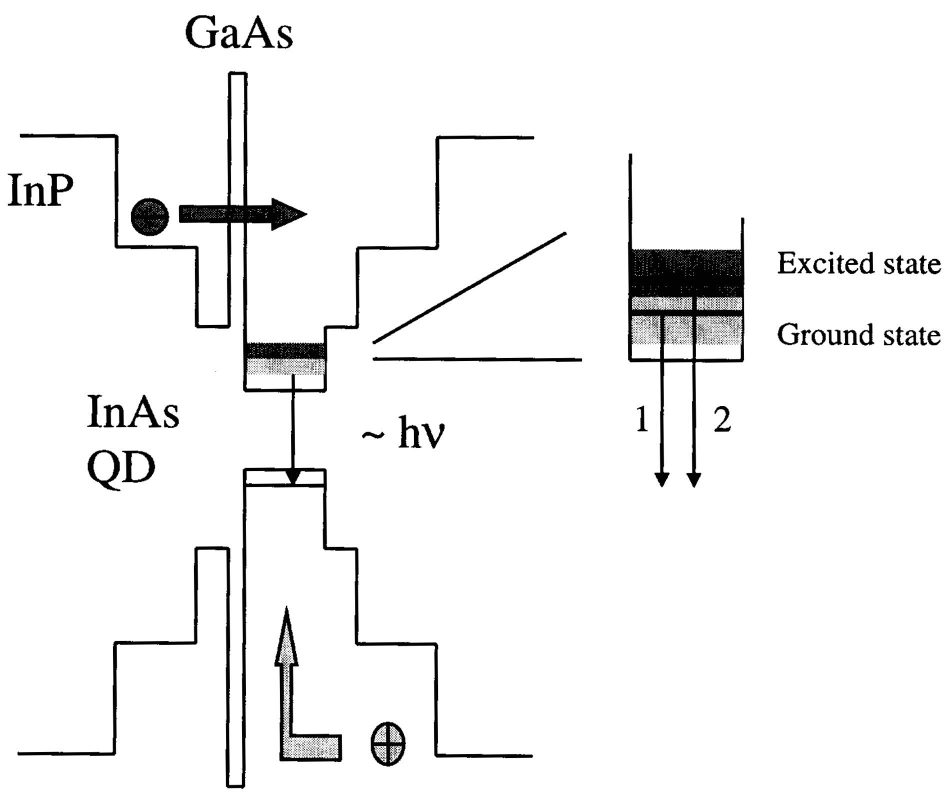

Figure 2, Yueming Qiu, Applied Physics Letters

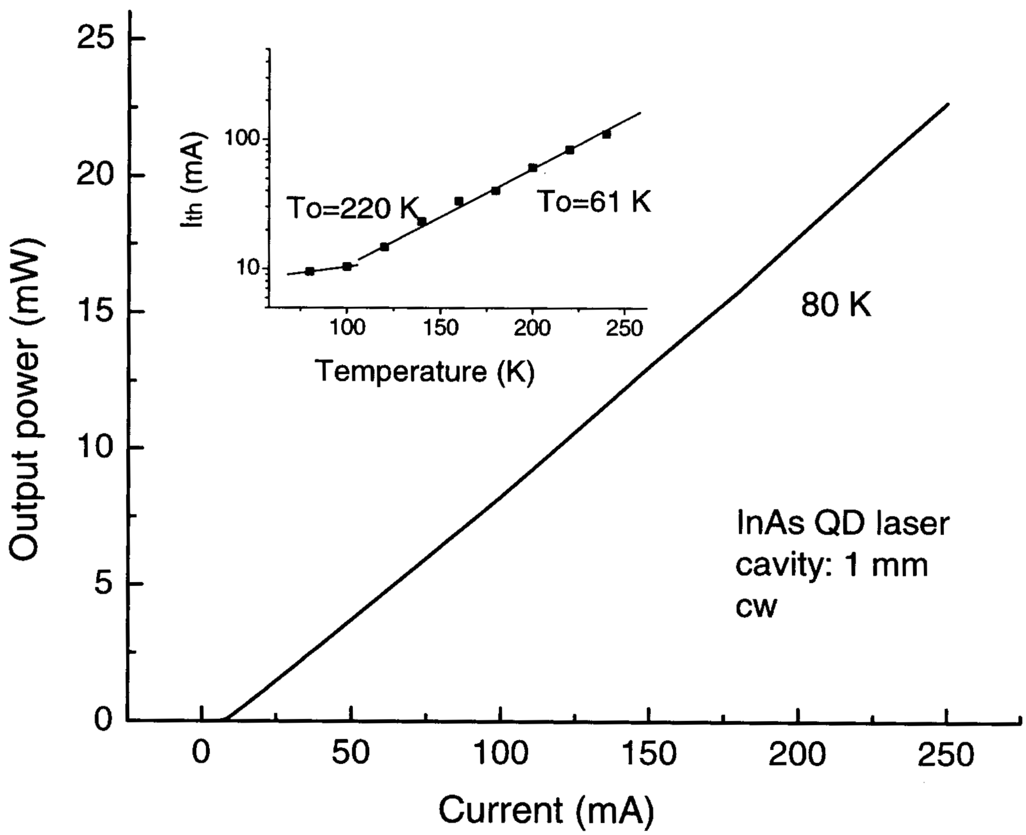

Figure 3, Yueming Qiu, Applied Physics Letters

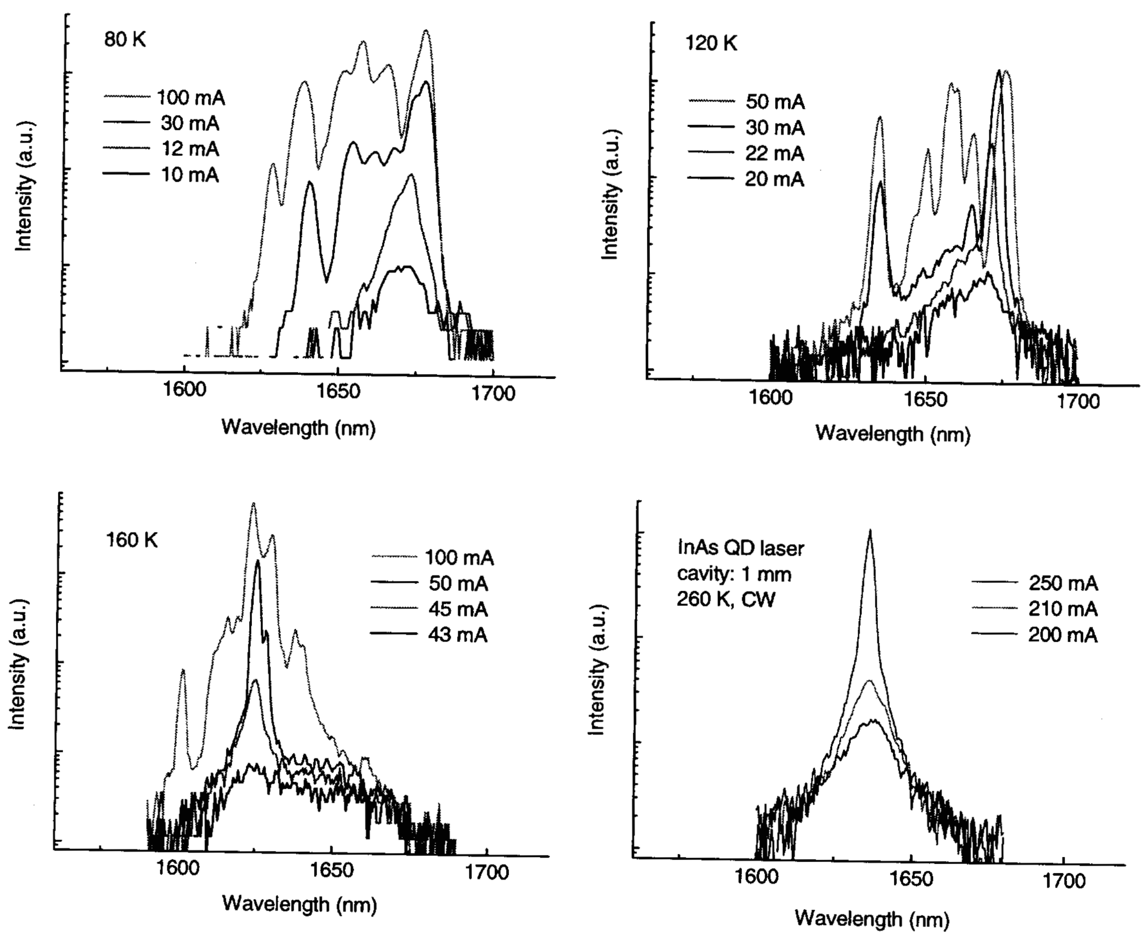

Figure 4, Yueming Qiu, Applied Physics Letters