Lasing from a single quantum wire

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A laser with an active volume consisting of only a single quantum wire in the 1-dimensional (1-D) ground state is demonstrated. The single wire is formed quantum-mechanically at the T-intersection of a 14 nm Al$_{0.07}$Ga$_{0.93}$As quantum well and a 6 nm GaAs quantum well, and is embedded in a 1-D single-mode optical waveguide. We observe single-mode lasing from the quantum wire ground state by optical pumping. The laser operates from 5 to 60 K, and has a low threshold pumping power of 5 mW at 5 K.

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A quantum wire laser is a novel semiconductor laser based on a 1-dimensional (1-D) active region such that the electron and hole carriers are allowed to move only in that one direction. In contrast, more familiar semiconductor lasers are 3-D double-hetero-structure lasers and 2-D quantum well lasers. Because the 1-D density of states (DOS) becomes more enhanced at the bottom of its band edge than the 2-D or 3-D DOS, a quantum wire laser is expected to show improvement in lasing performance.

However, fabrication of a single quantum wire that lases from the lowest quantum state of the wire is difficult. Indeed all quantum wire lasers so far reported are either multiple-wire lasers [1, 2, 3, 4], which have many quantum wires in the active region, or they are wide single-wire lasers which lase only in their excited-subband states [5, 6, 7, 8, 9, 10]. The excited-state lasing is typically characterized by a lasing energy above the energy of ground-state spontaneous emission at low pump levels. Since excited subbands allow motion of carriers in directions perpendicular to the axis of the wire, such excited-state wire lasing is not expected to have 1-D characteristics.

In this paper, we demonstrate a single quantum wire laser with only one 1-D subband, and observe stable single-mode lasing from this ground state subband of our quantum wire.

The single quantum wire laser is fabricated by an advanced crystal growth method called cleaved-edge overgrowth with molecular beam epitaxy (MBE) [14], in which two MBE growth steps are separated by an in situ wafer cleave. In the first MBE growth, we successively grew at 600 °C on a non-doped (001) GaAs substrate, a 500 nm GaAs buffer layer, a 1.5 μm Al$_{0.5}$Ga$_{0.5}$As cladding layer, a 250 nm Al$_{0.35}$Ga$_{0.65}$As barrier, a 14 nm Al$_{0.07}$Ga$_{0.93}$As quantum well (stem well), a 250 nm Al$_{0.35}$Ga$_{0.65}$As barrier, 1.5 μm Al$_{0.5}$Ga$_{0.5}$As cladding layer, and a 6.5 μm GaAs cap layer. Then, we cleaved the wafer in the MBE chamber, and grew at 490 °C on the newly exposed (110) edge, a 6 nm GaAs quantum well (arm well), a 10 nm Al$_{0.5}$Ga$_{0.5}$As barrier, a 111 nm Al$_{0.1}$Ga$_{0.9}$As core layer, a 960 nm Al$_{0.5}$Ga$_{0.5}$As cladding layer, and a 10 nm GaAs cap layer. After the growth of the arm well, we interrupted growth and annealed the GaAs surface for 10 minutes at 600 °C [15].

Figure 1 shows a schematic cross-sectional view of the single quantum wire laser structure. At a T-shaped inter-
section of a 14 nm-thick stem well and a 6 nm-thick arm well, quantum-mechanical confinement of electrons forms a quantum wire (T-wire). Contour curves in the blow up of the T-wire in Fig. 1 show the wave function of 1-D electrons. Previous experimental and theoretical studies \(^2\)\(^{16}\) show that such a T-wire has no confined higher 1-D electron subband, and is in the 1-D ground state quantum limit. A photoluminescence measurement shows that energies of the ground-state exciton in the T-wire, arm well and stem well are respectively 1.582, 1.602 and 1.636 eV at 5K. The single quantum wire is embedded in a core of T-shaped optical waveguide (T-waveguide). Contour curves at the top part of Fig. 1 show optical field intensity, or optical mode (transverse mode), for lasing. The curves at the top part of Fig. 1 show optical field intensity overlapped with the 14 nm density, or optical mode (transverse mode), for lasing. The curves at the top part of Fig. 1 show optical field intensity overlapped with the 14 nm density, or optical mode (transverse mode), for lasing.

A series of lasers each with 500 \(\mu\)m long optical cavities were cut from the wafer by (110) cleavage, and the cavity-mirror surfaces were coated by 120 nm- and 300 nm-thick gold layers with estimated reflectivities of 97 %. Each laser was pumped optically with cw titanium-sapphire-laser light, mechanically chopped into a 1 % duty ratio to minimize sample heating. The excitation light energy was 1.6455 eV. The pump laser light in a filament shape of about 1 \(\mu\)m width focused by a cylindrical lens and a 0.5 numerical aperture objective lens was incident on the top (110) surface of the sample illuminating the 500 \(\mu\)m long T-wire uniformly. Laser emission was detected via the 120 nm-thick gold mirror which has an estimated transmissivity less than 0.1 %.

Figure 2 shows typical laser emission spectra from a device at 5K for various excitation input powers \(P_{in}\). At an input power \(P_{in}=8.3\) mW, multi-mode laser emission of the T-wire is observed at 1.578 eV. It changes to single-mode at \(P_{in}=17\) mW, and shows a slight red-shift with mode hopping as the input power increases. The energy stability of our quantum wire laser with increasing pumping power is remarkable. The total red-shift from laser threshold to pumping at 260 mW or \(\times 50\) threshold is only 1.5 meV. The details of this small shift with increasing pumping power are seen most clearly in Fig. 3. Note that for all pumping powers the lasing energies lie just below the ground-state exciton (1.582 eV) in the T-wire, proving that the lasing indeed occurs in the T-wire ground state.

At higher energies, laser emission from the arm well and the stem well are also observed, as denoted in Fig. 2. Lasing by the arm well, shown with a magnified scale by a factor of 20, occurs only at very high pumping power \(P_{in}=260\) mW. It cannot occur for lower powers, since photo-excited carriers in the arm well readily empty into the T-wire. At \(P_{in}=260\) mW, however, the T-wire state saturates allowing the arm well to fill sufficiently to begin separately lasing.

Lasing by the stem well is also observed for input powers above \(P_{in}=17\) mW. Not surprisingly the emission is stronger than that of the T-wire, and is shown with a reduced scale by a factor of 1/150. In contrast to the case of the arm well, carrier flow from the stem well to the T-wire causes only a minor effect on carrier density in the stem well, since the excitation light generates carriers in the stem well over a large region extending many microns away from the T-wire. The stem well laser emission has multiple longitudinal modes. It shows a larger red-shift of 5 meV at \(P_{in}=260\) mW. The stem well lasing can be regarded as a prototype of a gain-guided 2-D quantum well laser.

It is interesting to compare the lasing of the T-wire with that of the stem well and the arm well, since it highlights in a single device intriguing differences in performance of a 1-D laser in comparison with 2-D lasers. First, the T-wire tends to lase in a single mode in contrast to multi-mode lasing of the arm and stem wells. This should be partly attributed to a 1-D optical waveguide, and to narrower gain spectra of the T-wire than those of the arm and stem wells. Second, the T-wire shows comparatively small red-shifts of 1.5 meV for increased input power \(P_{in}=260\) mW, while the stem well shows larger red-shift of 5 meV. This reflects difference in many-body Coulomb interaction effects in a 1-D wire and a 2-D well \(^3\). Third, the T-wire lasing has a lower threshold than the others. This last point is all the more remarkable since the T-wire laser has a small optical confinement factor \(\Gamma = 5 \times 10^{-4}\) in contrast to large \(\Gamma = 0.02\) in the stem well laser and \(\Gamma = 0.01\) in the arm well laser. Clearly the single T-wire laser has a high enough gain to compensate for the very low \(\Gamma\) factor. These three
features of the T-wire are also observed in single wire lasers we fabricated with 800 μm-long cavities and also in multiple wire lasers with 20 wires [10].

Figure 3 (a) shows lasing spectra of the T-wire more in detail for the various input powers up to $P_{in}=260$ mW. Though the width of each emission line is limited by the spectral resolution 0.2 meV of the spectrometer, the results reveal interesting details of longitudinal modes in the T-wire lasing, where modes a - e denote respective longitudinal lasing modes. Multi-mode lasing with several longitudinal modes centered at a starts at input power of $P_{in}=5$ mW. Transition from multi-mode lasing to single-mode lasing at b occurs at low input power of $P_{in}=10$ mW. Single mode lasing at such low input power is one of the remarkable characteristics of the T-wire laser. For increased input power, we observe mode hopping from b to c, to d, and to e with accompanying red-shifts. Below input power $P_{in}=130$ mW, lasing-mode separation, or mode hopping distance, is $\Delta E_1=0.30$ meV. This $\Delta E_1$ corresponds to the mode separation of a Fabry-Perot resonator with 500 μm cavity length, when the effective refractive index is 4.1. Above $P_{in}=130$ mW, however, it becomes $\Delta E_2=0.60$ meV. The reason of the doubled mode separation at high pumping is not understood.

Figure 3 (b) plots laser emission intensity of the T-wire at 5K as a function of input power. The inset shows magnified plots near threshold power of 5 mW.

For higher input powers above $P_{in}=20$ mW, laser emission intensities of the T-wire plotted by black dots and denoted as Total in Fig. 3 (b) increases showing irregular oscillations and dips. We also plot intensities of respective longitudinal modes a - e in T-wire lasing. It turns out that the dips in the total intensity occur exactly at those input powers where the laser switches from one lasing mode to the next. The reason for this interesting effect is also not at present understood.

Figure 4 (a) shows the laser emission spectra of the T-wire at 5, 20, 40 and 60K for input powers of 42 mW and 130 mW. Single-mode lasing is observed up to 40K, while only multi-mode lasing occurs up to 60K. With the increase in temperature, the spectral peaks are shifted toward lower energies as expected due to the shrinkage in the GaAs band-gap energy.

Figure 4 (b) plots laser emission intensity of T-wire at 5, 20, 40 and 60 K against input powers up to 100 mW. Notice that the lasing intensities at 20 K are larger than those at 5K. This is caused by enhanced carrier diffusion in the stem well and the arm well which provides more carriers to the T-wire at 20 K than at 5 K. At 40 K and 60 K, however, lasing intensities become smaller and the lasing threshold increases. This is probably because carriers in the T-wire are thermally activated to escape to distant regions of the arm well and the stem well.

In summary, we fabricated a single quantum wire laser in the 1-D quantum limit. We observed lasing at the ground state of a 14 nm × 6 nm wire at 5 - 60 K via optical pumping. It shows a low threshold input power of 5 mW at 5 K.

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