Interband Cascade Lasers at Long Wavelengths

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Abstract: We report the demonstration of InAs-based interband cascade lasers in a temperature range from 80 to 260 K operating in pulsed and continuous wave modes at wavelengths near 6.0, 7.4, and 10.3 microns.
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It has been a challenge for conventional interband diode lasers to extend their lasing wavelength to longer than 6 m due to several issues including: limitations of materials of suitable bandgap, increased free-carrier absorption loss, and Auger recombination. Although IV-VI lasers can lase beyond 6 µm, their continuous wave (cw) operation is limited to cryogenic temperatures (<160 K) [1] with low output power (<1 mW) and relatively high threshold current. In principle, interband cascade (IC) lasers [2] based on a type-II quantum well (QW) active region can be tailored to lase at very long wavelengths, not limited by the bandgap of the continuant material. The lasing wavelength achieved for a type-II QW laser relies on the gain attainable with a reduced wave-function overlap, band filling, as well as adequate waveguide cladding layers. IC lasers have been demonstrated with efficient cw operation above room temperature in the 3-4 µm wavelength region with a low threshold current density [3-6], which alleviates the band-filling effects and reduces the free-carrier absorption losses. As such, it is possible for IC lasers to operate at longer wavelengths, particularly with the use of plasmon waveguide structures, which bring additional benefits including: simplified epitaxial growth, improved thermal dissipation and optical wave confinement [7-9]. Our initial efforts demonstrated plasmon-waveguide IC lasers at wavelengths as long as 7.5 µm [8]. Here, we report the demonstration of InAs-based plasmon IC lasers near 6.0 and 7.4 microns with significant improvements in threshold current density, operating temperature, and with extended wavelength coverage to 10.4 µm.

Four IC laser structures (wafers R064, R065, R066, R069), consisting of 15 cascade stages, were grown in an Intevac Gen II molecular beam epitaxy (MBE) system on *n*-type InAs (001) substrates with an n^{++}-type InAs bottom cladding layer (1.6-2.0-µm-thick) and with a Si-doping concentration of $7\text{-}10\times10^{18}$ cm^{-3}, depending on designed lasing wavelength. Wafer R067 and R068 nominally have the same cascade region, which is different from wafers R064 and R069. Compared to earlier reported plasmon-waveguide IC lasers [7-9], for the four laser structures the electron injector is shorter, and the hole injector is enhanced with two QWs [4] for suppressing the leakage current. In all the structures, the cascade region was designed and grown with Al(Ga)As interfaces to achieve strain-balance.

After growth, the wafers were processed into ridge-waveguide lasers of various widths (15, 20, 30 and 40 µm), with a SiO_2 insulation layer and metal contact (200-250 nm thick) on the top layer and a similar metal contact to the back of the substrate. The top metal contact window is about 2-3-µm wide near the edges (for 20, 30, 40-µm-wide ridges) or near the center (for 15-µm-wide ridge). As such, the SiO_2 insulation layer underneath the contact metal pad covers the majority of the laser ridge and serves as the cladding layer for the laser. The processed wafers were cleaved into laser bars with cavity lengths of 1-3 mm with facets left uncoated and mounted epi-side-up on copper heat-sinks for measurements.

From wafer R067, a 15-µm-wide and 0.8-mm-long device lased at 211 K in cw mode, and a 20-µm-wide and 1.4-mm-long device lased near 6.0 µm at temperatures up to 210 K in cw mode (Fig. 1) and 260 K in pulsed mode (Fig. 2), which is higher than the maximum cw and pulsed operating temperature of 184 and 210 K, respectively, for earlier IC lasers at similar wavelengths (5.9 µm) [9]. A 20-µm-wide and 1.4-mm-long device from wafer R068 lased near 6.3 µm at temperatures up to 200 K in cw mode (Fig. 1). Devices from R068 had a lower threshold current density than devices from R067 (J_{th}~6 A/cm^2 at 80 K and 220 A/cm^2 at 200 K versus J_{th}~8 A/cm^2 at 80 K and 270 A/cm^2 at 200 K for 20-µm-wide devices) and thus should lase at higher temperatures, but these were easily damaged at higher currents, which limited their maximum operating temperature.

A 15-µm-wide and 1.6-mm-long device from wafer R064 lased in cw mode at temperatures up to 189 K near 7.4 µm (Fig. 1), which is higher than the earlier record of 141 K for IC lasers at similar wavelengths (7.2 µm) [9]. In pulsed mode, this device lased at temperatures up to 200 K near 7.4 µm (Fig. 2). A 20-µm-wide and 1-mm-long device from wafer R069 lased in cw mode at temperatures up to 166 K near 10.3 µm (Fig. 1), the longest lasing wavelength achieved among III-V interband lasers. The emission wavelength of the laser was near 9.0 µm (Fig. 1) at low temperatures (≤125 K) and then hopped to near 10.3 µm at higher temperatures (≥150 K). Under certain operating current levels at temperatures between 125 and 145 K, simultaneous lasing at both wavelengths near 9.1 and 10.2 µm was observed. At this moment, why such a mode hop occurred is not clear; this phenomenon will be further investigated and reported in the future. In pulsed mode, the device lased at temperatures up to 190 K near 10.4 µm with a threshold current density of 970 A/cm^2 (Fig. 2). Emission wavelength hopping also occurred in pulsed operation around 150 K.

Devices from all wafers exhibited a very low threshold current density at low temperatures (*e.g.*, 6-10 A/cm^2 at 80 K), with little sensitivity to the lasing wavelength. A 40-µm-wide device from R068 showed a threshold current density as low as 4.4 A/cm^2 at 80 K. The output power in cw mode exceeded 10 mW/facet. More details and the latest results will be reported at the conference.

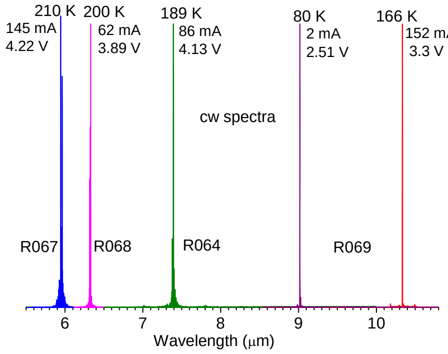

Fig. 1. Cw lasing spectra for ridge waveguide IC lasers from wafers R067, R068, R064 and R069 at several temperatures.

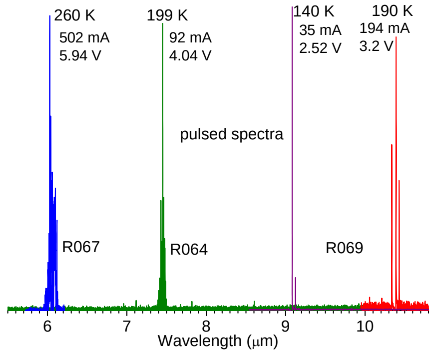

Fig. 2. Pulsed lasing spectra for ridge waveguide IC lasers from wafers R067, R064 and R069 at several temperatures.

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