Terahertz frequency quantum cascade lasers operating up to 178 K with copper metal-metal waveguides

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***Abstract*—We report terahertz frequency quantum cascade lasers operating up to a record temperature of 178 K, employing a three-quantum-well active region design and copper metal-metal waveguides. Their performance is compared to devices with gold metal-metal waveguides.**

I. Introduction And Background

Terahertz (THz) quantum cascade lasers (QCLs) are rapidly filling the so-called THz gap in the electromagnetic spectrum, following their initial demonstration in 2002. The first THz QCLs [1] were based on a chirped-superlattice active region design and a semi-insulating surface-plasmon waveguide, and operated up to a maximum operating temperature (T_{max}) of 50 K in pulsed mode. Optimized active region designs and use of metal-metal (MM) waveguides with, initially, indium-gold and, subsequently, copper-copper thermocompression bonding [2], have since led to the highest recorded T_{max} of 169 K [2]. In these structures, a layer of gold was used as the upper cladding layer to confine the lasing modes.

Here, we demonstrate that T_{max} can be enhanced further through use of copper for both upper and lower cladding layers, principally as a result of the superior optical properties of copper in the THz frequency range.

II. Results

A THz QCL was grown by molecular beam epitaxy containing a three-quantum-well active region based on the structure reported by Luo *et al.* [3], but with the active region sheet doping density reduced from 3.6×10^{10} cm^{-2} to 2.75×10^{10} cm^{-2} per module. Using specific calibration wafers, pyrometric interferometry was used to set gallium and aluminium fluxes to an accuracy of $< \pm1.5\%$ prior to growth, with post-growth measurements confirming that these fluxes had drifted by $< \pm2\%$ throughout the active region.

Following growth, the material was processed into MM waveguides [2]. Two sets of devices were processed, with gold and copper metal cladding. Our calculations, undertaken for 10-µm-thick and infinitely wide MM waveguides, indicate that the waveguide losses in MM waveguides with copper cladding are significantly smaller than those in MM waveguides with gold cladding (Fig. 1(a)).

For testing, devices were placed in a helium-flow cryostat and driven in pulsed mode with 30 ns pulses at a 1 kHz repetition rate. Peak powers were measured with a calibrated helium-cooled bolometer. Current density-voltage characteristics and an emission spectrum of a typical MM waveguide device with gold cladding layers are shown in Fig. 1(b). Devices with gold MM waveguides operated up to 168 K (Fig. 1(c)), higher than the T_{max} = 142 K reported in the original paper using a similar MM fabrication scheme [3]. The increased maximum operating temperature might be a result of higher growth quality, reduced doping density, or optimized fabrication procedures. Devices with copper MM waveguides operated up to 178 K, the highest reported operating temperature for a THz QCL to date (Fig. 1(d)) [4]. The improvement in temperature performance in copper MM waveguide devices results from the superior optical properties of copper over those of gold (Fig. 1(a)).

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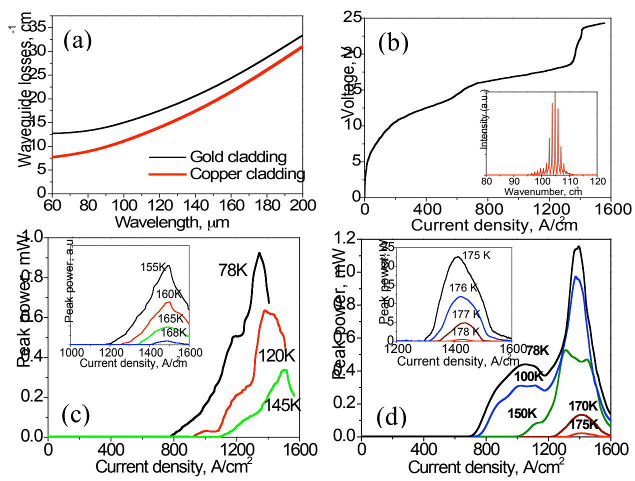

Fig. 1. (a) Calculated waveguide losses in a 10-µm-thick MM waveguide assuming an infinite width and an average active region doping of 5×10^{15} cm^{-3}. (b) Current density-voltage characteristics and an emission spectrum of a representative device with gold MM waveguide. (c) and (d) Light intensity-current density (L-I) characteristics of the best-performing device with a gold and copper MM waveguide, respectively. Inset: L-I characteristics of the devices close to the maximum operating temperatures.

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