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Silver-based surface plasmon waveguide for terahertz quantum cascade lasers

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1. Introduction

Terahertz quantum cascade lasers (THz QCLs) have undergone rapid developments since their first demonstration in 2002 [1]. Presently, the wide spectral range (1.2–5.2 THz) [2, 3] and high output power (1 W) [4] make THz QCLs promising sources for applications in high-resolution spectroscopy and THz imaging. However, their maximum operating temperature is only 199.5 K [5] and therefore cryogenic cooling is still needed. Improving the thermal performance of THz QCLs is a key challenge for their practical usage.

The waveguide loss is closely related with the device thermal performance. To lower the loss, copper has been used to replace the gold in the standard metal–metal waveguide scheme, and around 10 K increase in the maximum lasing temperature has been achieved [6, 7]. Here, we employ silver as the waveguide metal and investigate its effects on devices with a single surface-plasmon waveguide configuration.

2. Experiments and results

The active regions of the THz QCLs were sandwiched by n-type GaAs layers. The bottom layer was 600-nm thick with Si doping concentration of 2×10^{18} cm^{-3}, and the top layer was 50 nm with doping of 5×10^{18} cm^{-3}. The whole structure was grown on a semi-insulating GaAs substrate using MBE. Pairs of nominally identical laser ridges, with four different active region designs (labeled A1, A2, B1 and B2) were fabricated; eight lasers in total. Pairs A1 and A2 are based on the resonant-phonon design [5], with a larger oscillator strength for A2. Pairs B1 and B2 are based on a hybrid design (i.e., interlaced bound-to-continuum and resonant phonon [8]), with higher doping in the active region of B2. Ridges were defined by wet chemical etching and AuGeNi electrical contact layers were deposited. Waveguide metal layers were deposited on top of the laser ridge and the backside of substrate, using Au for one device in each pair, and Ag for the other. Ti/Ag/Ti/Au (10/200/10/80 nm) layers were used for Ag-based waveguides while Ti/Au (10/150 nm) were used for gold-based waveguides. The devices were mounted on the cold finger of a helium-cooled cryostat and characterized using an FTIR spectrometer and a Ge:Ga bolometer.

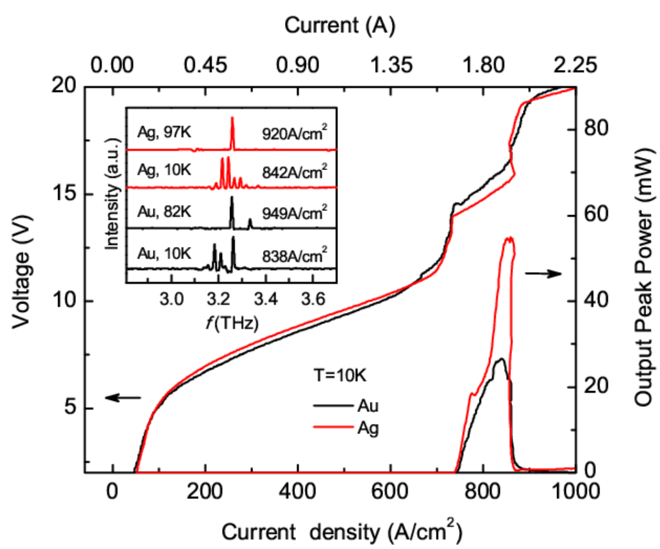

Fig. 1. LIV curves of QCLs (pair A1) with Ag and Au waveguide layers at 10 K. Inset are the spectra at 10 K and at the maximum operating temperatures. The devices are 1500-μm long and 150-μm wide, and are driven by 2-μs wide current pulses with a duty cycle of 2%.

Figure 1 shows the THz-power–current–voltage (LIV) plots and the spectra of two QCLs (pair A1). Except for the waveguide metal layers, all parameters were identical for each device within a pair. The Ag-based QCL has a higher maximum operating temperature and higher output power than the otherwise identical Au-based device. These improvements are attributed to the decrease in the waveguide loss. The spectra of the two devices are similar, indicating only a small variation in the peak net gain.

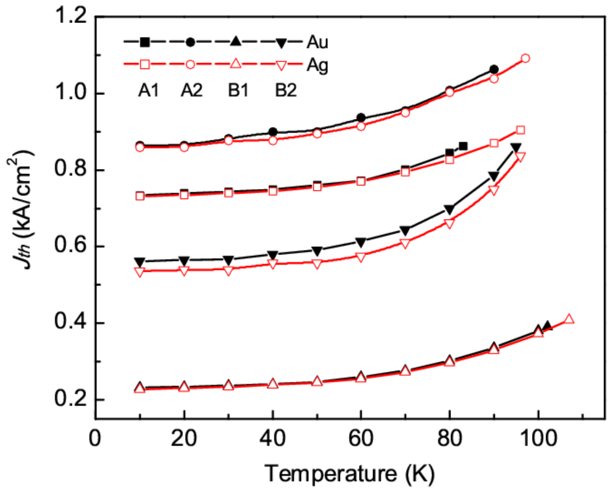

Fig. 2. The threshold current density of four pairs of QCLs versus heat-sink temperature. For each pair of devices, the only difference is the waveguide metal layer. The device dimensions are 1500×150 μm^2 for pairs A1, A2 and B2, and 3000×150 μm^2 for pair B1.

The thermal evolution of the threshold current density is compared in figure 2 for each pair of devices. All the Ag-based devices have a higher maximum lasing temperature and a lower threshold current density than the equivalent Au-based devices, indicating that silver waveguides can improve the thermal performance of THz QCLs. The magnitude of the effect is dependent on the active region design and the doping level, with stronger effects being observed in the designs with smaller oscillator strength (A1) and lower doping concentration (B1).

These results indicate that silver-based devices exhibit superior thermal performance to equivalent gold-based devices, with the magnitude of the improvements being dependent on the active-region design. The waveguide analysis and the effects of different active region designs, such as bound-to-continuum and scattering assisted injection, will be discussed.

Acknowledgments

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