

Quantum cascade lasers with double metal-semiconductor waveguide resonators

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Quantum cascade (QC) lasers with double metal-semiconductor waveguide resonators are reported for operating wavelengths of 19, 21, and 24 μm . The waveguides are based on surface-plasmon modes confined at the metal-semiconductor interfaces on both sides of the active region/injector stack and are not restricted by a cutoff wavelength for the TM polarized intersubband radiation. The double metal-semiconductor resonator devices are fabricated using an epilayer transfer process. Optical confinement factors close to 1 are obtained, with low waveguide losses. The performance of the devices is compared with that of QC lasers based on single-sided surface-plasmon waveguides. The concept of QC laser with double metal-semiconductor waveguide is applicable to a much wider wavelength range. © 2002 American Institute of Physics. [DOI: 10.1063/1.1469657]

Recent research on quantum cascade (QC) lasers has led to an impressive extension of the frequency range,¹⁻³ as well as in overall device performance. In the midinfrared range higher operating temperatures and optical power, and ultra-high-speed operation and mode locking have been achieved.⁴ Recently, QC lasers operating at very long wavelengths at 21.5 and 24 μm were reported, and cw operation was demonstrated for a surface-plasmon QC laser operating at $\lambda=19 \mu\text{m}$.^{1,2} While the QC laser scheme is in principle well scalable to even longer wavelengths on the other side of the Reststrahlenband, fast nonradiative relaxation rates and increased free carrier absorption make this difficult. Furthermore, the required thickness of the epilayers for dielectric waveguiding is roughly proportional to the operating wavelength, thus leading to very thick epitaxial layers.

The realization of long-wavelength QC lasers was therefore strongly helped by the introduction of surface-plasmon waveguides. In addition, these waveguides are not restricted by a cutoff wavelength for TM polarized light, thus allowing an application even for very long wavelengths.⁵

In the QC lasers with single-sided surface-plasmon waveguides,^{1-3,6} the modes were guided by the metal of the top contact. Additional dielectric confinement of the mode at the substrate side was achieved by the refractive index contrast between the InGaAs/InAlAs layer and the InP substrate. The bottom confinement still allows a certain overlap of the mode with the substrate and special attention has to be paid to keep the additional waveguide losses small. Free carrier absorption in the substrate turns out to be a significant contribution to the losses: in Ref. 1 this problem was addressed with the realization of a double-sided surface-plasmon waveguide for a 21.5 μm laser by inserting a 750-nm-thick highly doped InGaAs plasmon layer between the active region and the InP substrate.¹ However, an increase in threshold was observed for this device resulting from the penetration of the

mode into the n^{++} layer. Calculations show in fact that, although the highly doped n^{++} layer could ideally behave as a perfect “metal,” for realistic doping levels the mode always penetrates the n^{++} layer, causing an increase in the waveguide losses.

A solution to this problem at long wavelengths can be obtained by a double metal cladding, which delivers a high confinement factor ($\Gamma \approx 0.98$) and low waveguide losses. In the case of a double metal-semiconductor waveguide the losses are only determined by the free carrier absorption in the active region and by the penetration of the mode into the metal layer, which decreases with increasing wavelength.⁷

In this letter we present the realization of QC lasers with double metal-semiconductor waveguide resonator operating at 19, 21, and 24 μm emission wavelengths. The emission energies are very close to the Reststrahlenband for InGaAs and have been chosen to lay at pronounced minima of the InGaAs two-phonon absorption spectrum.⁸ In addition, the doping densities in the injectors have been kept reasonably low ($n_s = 1.5 \times 10^{11} \text{ cm}^{-2}$) to reduce free carrier absorption.

All three laser structures have been grown by molecular beam epitaxy using lattice matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ on InP substrate. The active regions and injectors, which are identical to the ones used in Refs. 1 and 2, were embedded between two 400-Å-thick InGaAs layers n doped to $1 \times 10^{17} \text{ cm}^{-3}$ and sandwiched between two n^{++} InGaAs layers (100-Å-thick on top, 200-Å-thick on bottom) for contact purposes. 75 periods have been grown for the $\lambda=19 \mu\text{m}$ structure, and 80 periods each for the $\lambda=21$ and $\lambda=24 \mu\text{m}$ ones. The total thickness of the epitaxial layers was between 5.9 and 6.24 μm [a schematic of the sample layer sequence is shown in the inset of Fig. 1(b)].

For the realization of the double metal-semiconductor waveguide an epilayer transfer process was employed. As a first step, the wafers were cleaved into 6×12 mm large pieces and metallized at the epilayer surface with a 2- μm -thick gold layer: this is one of the two surface-plasmon-carrying layers and, at the same time, the wafer-bonding layer. The samples were then pressure bonded at 210 °C with

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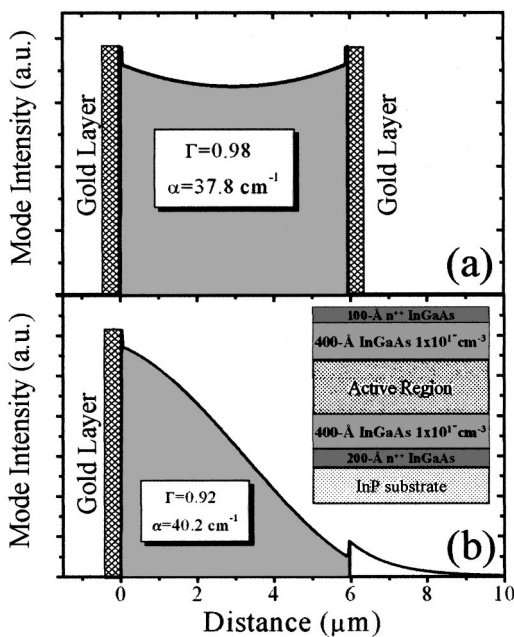


FIG. 1. (a) Intensity profile of the surface-plasmon mode for the $\lambda=21 \mu\text{m}$ laser with double metal-semiconductor waveguide; (b) intensity profile of the surface-plasmon mode for the $\lambda=21 \mu\text{m}$ laser with single-sided surface-plasmon waveguide; inset: schematic of the layer structure.

an In/Pb alloy (30% Pb) to GaAs substrates which had previously been evaporated with a 1500-nm-thick Au layer. Finally, the InP substrate was mechanically thinned and then completely removed by selective etching with 35% HCl. This wet-etch process stops at the bottom 200-Å-thick n^{++} InGaAs layer and therefore only the InGaAs/AlInAs epilayers bonded to the GaAs substrates are left. On this sample, that is the QC laser active region bonded to a GaAs substrate, device processing was then performed.

Conventional laser ridges of various widths (30–45 μm) were defined by optical contact lithography and wet-chemical etching. The ridges were etched approximately through the thickness of the total epilayer. Instead of the standard SiO_2 or SiN (Ref. 9) an 800-nm-thick chalcogenide layer (GeSSe) was laser deposited as insulator. After opening a window into the insulation layer, a Ti/Au top contact was deposited, leaving a wide portion of the top of the ridges open for the deposition of a second, 300-nm-thick surface-plasmon-carrying gold layer. The devices were then cleaved into laser bars and soldered to copper blocks, or removed from the GaAs substrates and directly attached to the copper block. Wires were finally attached to the top contact with a conducting silver epoxy, in order to avoid ultrasonic bonding.

Our devices consist of the active material embedded between very thin (100–400 Å) InGaAs layers and the top and bottom metal layers. The total thickness is around 8 μm . The vertical intensity profile of the mode [shown in Fig. 1(a) for the $\lambda=21 \mu\text{m}$ laser] was calculated using a transfer-matrix technique. The dielectric constants for the doped semiconductor layers were calculated using a Drude–Lorentz model, while the ones for gold were taken from Ref. 10. As expected, a very high confinement factor is obtained ($\Gamma=0.98$), and waveguide losses of $\approx 38 \text{ cm}^{-1}$. The calculated intensity profile of the surface-plasmon mode for a $\lambda=21 \mu\text{m}$ laser

with the conventional single-sided surface-plasmon processing^{1,6} is shown in Fig. 1(b). The low-doped ($n = 1-4 \times 10^{17} \text{ cm}^{-3}$) InP, due to its lower refractive index compared to that of the InGaAs/AlInAs layers, actually provides a good optical confinement ($\Gamma=0.92$) with low waveguide losses ($\alpha_w \approx 40 \text{ cm}^{-1}$), despite the presence of the 200-Å-thick n^{++} bottom contact layer.

The two waveguiding approaches have therefore almost equivalent performance: the penetration depth into the metal layer is small enough making a double metal-semiconductor waveguide possible, but at the same time confinement through the low-doped InP substrate is still a viable solution. With increasing wavelengths, however, the performance of the double metal-semiconductor waveguide improves, while for the single-sided surface-plasmon waveguide the penetration of the mode into the doped substrate leads to an increase of the optical loss. The double metal-semiconductor waveguide makes it thus possible to use the same waveguide concept from the far-infrared wavelength range to the millimeter wave range.

Figure 2 shows the threshold current density as a function of temperature for two QC lasers emitting at $\lambda=21 \mu\text{m}$ and processed with a double metal-semiconductor waveguide (filled circles), and a single-sided surface-plasmon waveguide (open squares), respectively. Typical low temperature (5 K) laser emission spectra for all the QC lasers realized with a double metal-semiconductor waveguides are reported in the insets of Fig. 2. The temperature behavior is similar in the two cases, in agreement with the similar waveguide losses, but the double metal-semiconductor device exhibits a slightly lower maximum temperature of operation (170 K instead of 180 K), probably due to worse thermal sinking. In addition the devices mounted directly on copper showed only a slightly improved thermal performance than the ones mounted on GaAs substrate, showing that the limiting factor is the thermal resistance of the bonding layer, not the conductance of the substrate material. A 21.5 μm QC laser with a double-sided surface-plasmon waveguide, where the low-doped buffer layer is replaced by a highly doped n^{++} -InGaAs, was previously realized (see Ref. 1). Its threshold current density (marked by an arrow in Fig. 2) was much higher, in accordance with waveguide losses calculations, due to the penetration of the mode into the highly lossy n^{++} layer: the double metal-semiconductor waveguide completely solves this problem and it seems a much better waveguide for an extension to even longer wavelengths, into the THz range.

Figure 3 shows the light-output and voltage versus current ($L-V-I$) characteristic of a 21 μm QC laser with single-sided surface-plasmon waveguide [Fig. 3(a)] and double metal-semiconductor waveguide [Fig. 3(b)], respectively. The maximum power emitted by the two devices is similar, we estimate a few mW (the power scale is the same for both the panels). This demonstrates that, for wavelengths around and above 20 μm , the double metal-semiconductor waveguide is performing well, and is comparable to the single metal one. In addition, this is a confirmation of our calculations, which show that the losses and hence the threshold current densities and slope efficiency of the two different waveguides should be very similar at these wave-

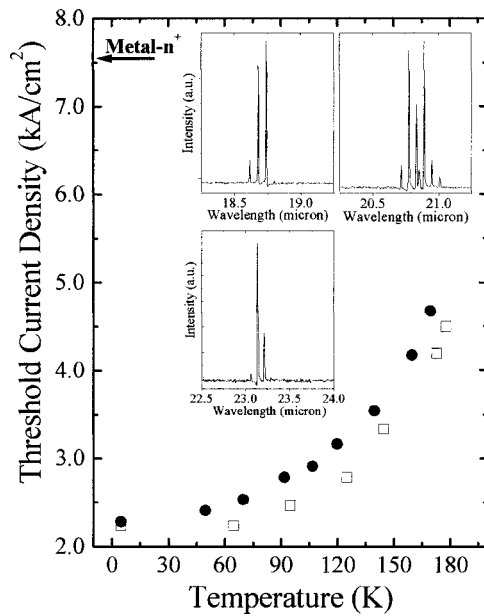


FIG. 2. Temperature dependence of the threshold current density of a QC laser at 21 μm wavelength with double metal-semiconductor waveguide (full circles) and single-sided surface plasmon waveguide (open squares). Devices are 36 μm wide and 800 μm long. The arrow indicates the low-temperature threshold current density of an identical device with a double-sided surface plasmon waveguide (Ref. 1) i.e., where a very thick n^{++} bottom layer acts as a "metal." Measurements were performed in pulsed mode (25 ns pulse width, 25 kHz repetition rate). Optical emission was detected with a He-cooled silicon bolometer. Inset: pulsed (30 ns pulse width, 100 kHz repetition rate) emission spectra of all the devices realized with double metal-semiconductor waveguide. The spectra were measured in rapid scan using a Nicolet Fourier transform infrared spectrometer and a DTGS detector. The spectral resolution was set to 0.125 cm^{-1} .

lengths. The L - I characteristics show that for low currents the light output of the double metal-semiconductor waveguide laser is actually higher than that of the single-sided surface-plasmon one. At higher drive currents instead the light intensity of the double metal-semiconductor device drops faster than that of the single-sided one. The effect can not be attributed to premature misalignment of the structure following the higher differential resistance [Fig. 3(b)], since the additional voltage falls on the contact (that is responsible for the increased resistance) and not on the device. We attribute this phenomenon to device heating problems: the increased dissipation is due to the decreased thermal properties of the double metal-semiconductor device, which results from not ideal bonding of the metallized interfaces. To support this, the duty cycle was varied and the results showed indeed that heat dissipation is limiting the device performance even for very short pulse lengths (≈ 100 ns). As a matter of fact, the volume for initial heat dissipation is very small for the double metal-semiconductor device and the slow heat conduction to the substrate (or to the copper) through the bonding layer induces a fast rise of the temperature in the active region. An improved pressure bonding process may be a possible solution to this drawback.

In conclusion, we have demonstrated a QC laser with a double metal-semiconductor waveguide. The naturally TM polarized light from intersubband transitions in QC lasers

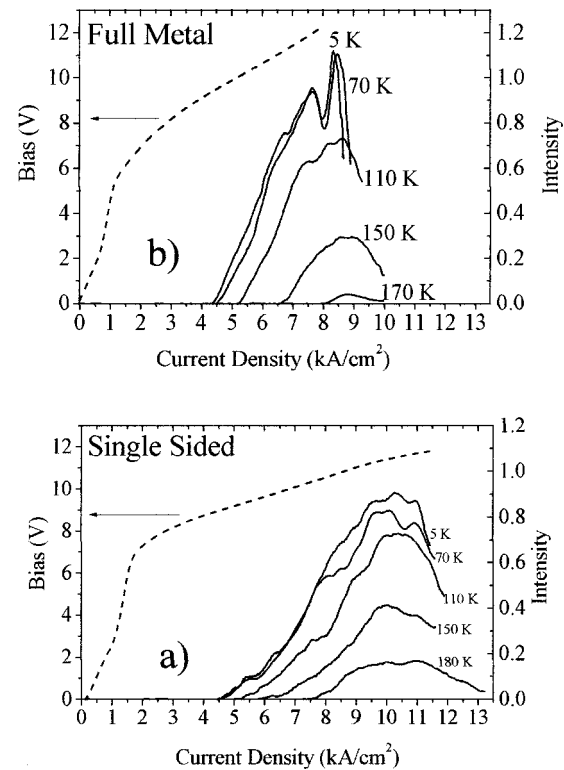


FIG. 3. L - I - V characteristics of a 21 μm QC laser with a single-sided surface-plasmon waveguide double metal-semiconductor waveguide (a) and (b). Lasers were operated in pulsed mode (50 ns pulse width, 5 kHz repetition rate) and a LN₂-cooled HgCdTe detector was used. The dashed line is a low-temperature (8 K) current-voltage curve for the same devices.

allows the application of this thin metal waveguide without the restriction of a cutoff wavelength. The performance of the waveguide, which is in very good agreement with calculations for wavelengths up to 24 μm , should only increase with wavelength thus showing that the concept of QC lasers together with this new waveguide can bridge the gap to the millimeter wave electronics.

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- ¹R. Colombelli, F. Capasso, C. Gmachl, A. L. Hutchinson, D. L. Sivco, A. Tredicucci, M. C. Wanke, A. M. Sergent, and A. Y. Cho, *Appl. Phys. Lett.* **78**, 2620 (2001).
- ²R. Colombelli, A. Tredicucci, C. Gmachl, F. Capasso, D. L. Sivco, A. M. Sergent, A. L. Hutchinson, and A. Y. Cho, *Electron. Lett.* **37**, 1023 (2001).
- ³A. Tredicucci, C. Gmachl, M. Wanke, F. Capasso, A. L. Hutchinson, D. L. Sivco, S. G. Chu, and A. Y. Cho, *Appl. Phys. Lett.* **77**, 2286 (2000).
- ⁴F. Capasso, R. Colombelli, R. Paiella, C. Gmachl, A. Tredicucci, D. L. Sivco, and A. Y. Cho, *Opt. Photonics News* **12**, 40 (2001); D. Hofstetter, M. Beck, T. Aellen, J. Faist, U. Oesterle, M. Illegems, E. Gini, and H. Melchior, *Appl. Phys. Lett.* **78**, 1964 (2001).
- ⁵P. Yeh, *Optical Waves in Layered Media* (Wiley, New York, 1988).
- ⁶A. Tredicucci, C. Gmachl, F. Capasso, D. L. Sivco, A. L. Hutchinson, and A. Y. Cho, *Appl. Phys. Lett.* **76**, 2164 (2000), and references therein.
- ⁷J. I. Pankove, *Optical Processes in Semiconductors* (Prentice-Hall, London, 1971).
- ⁸E. S. Koteles and W. R. Datars, *Can. J. Phys.* **54**, 1676 (1974); *Solid State Commun.* **19**, 221 (1976).
- ⁹C. Sirtori, C. Gmachl, F. Capasso, J. Faist, D. L. Sivco, A. L. Hutchinson, and A. Y. Cho, *Opt. Lett.* **23**, 1366 (1998).
- ¹⁰M. A. Ordal, L. L. Long, R. J. Bell, S. E. Bell, R. W. Alexander, Jr., and C. W. Ward, *Appl. Opt.* **22**, 1099 (1983).

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