Low-threshold vertical cavity surface-emitting lasers with metallic reflectors

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Continuous-wave room-temperature operation is reported for the first time of vertical cavity current injection semiconductor lasers with a metallic reflector. The GaAs/(AlGa)As lasers have low-threshold currents of 8 mA for 8-μm-diam contacts and threshold current densities of 9.5 kA/cm^2. Single longitudinal mode and bimodal operation are obtained for short and long Fabry–Perot étalons, respectively. The spectral width of the single-mode laser line is 0.1 Å. The laser structures have a very small series resistance which results in a voltage drop of 1.8 V along the diodes at lasing threshold.

The optical axis of vertical cavity surface-emitting lasers (VCSELs) is along the epitaxial growth direction of the semiconductor crystal as opposed to the more common horizontal cavity lasers or edge-emitting lasers. Due to the short gain path of vertical cavity lasers, it is required that the reflectivity of the mirrors defining the Fabry–Perot étalon is close to unity. Several concepts were employed to achieve a high reflectivity including metallic reflectors,[1–3] quarter-wave (λ/4) semiconductor multilayer reflectors,[4,5] quarter-wave dielectric reflectors,[6–8] and a hybrid mirror, i.e., a combination of the metallic and λ/4 semiconductor reflectors.[9] The requirement of high reflectivity makes the concept and fabrication of the two mirrors a key point for vertical cavity lasers.

The concept of the metallic reflector is of crucial importance due to its ambivalent requirements. The metallic contact serves two purposes, that is, as a mirror as well as an ohmic electrical contact. The parallel direction of optical propagation and current density vector in vertical cavity lasers requires the simultaneous realization of the reflector and contact. This property is unique to vertical cavity lasers and is in contrast to horizontal cavity lasers where the light and current vectors are orthogonal. The contact is a nonalloyed ohmic contact[10] which is typically achieved by a high doping concentration in the vicinity of the metal-semiconductor junction. Such nonalloyed ohmic contacts have a smooth morphology due to the lack of thermal annealing. The metallic mirror/contact concept has a number of advantages including low series resistance,[1] low thermal resistance,[1] and small current spreading due to the proximity of active layer and the contact. A planar laser structure can be realized with such reflectors.

In this letter we report on a metallic reflector vertical cavity laser using silver (Ag) for the top reflector and contact. The lasers have excellent properties including low-threshold current, narrow linewidth, low series resistance, and small thermal resistance. The structure of the laser, the corresponding band diagram, and the profile of the refractive index are shown in Fig. 1. The laser structure consists of 30 pairs of an n^+-AlAs/Al$_{0.05}$Ga$_{0.95}$As (730 Å/600 Å) quarter-wave multilayer structure, a lower confining n^--Al$_{0.20}$Ga$_{0.80}$As layer, a 0.6 μm p^--GaAs active region, a 0.5 μm top confining p-Al$_{0.30}$Ga$_{0.70}$As layer, and a 625-Å-thick p^+-Al$_{0.10}$Ga$_{0.90}$As contacting layer. The thickness of the lower confinement layer was chosen to be 3 and 13 μm for two different samples.

The epitaxial films are grown on (001) oriented n^+-type GaAs substrates in a Varian Gen II molecular beam epitaxy system. The surface morphology of the crystals is examined by Nomarski contrast microscopy and is found to be featureless except for oval defects. Transmission electron microscopy revealed planar growth of the AlAs/Al$_{0.05}$Ga$_{0.95}$As quarter-wave reflectors and no roughness even after 30 periods. Silver (2000 Å) is evaporated after growth in a separate high vacuum chamber as the initial processing step. The Ag dots are photolithographically defined and undesired Ag is removed by etching with diluted nitric acid. Some of the laser samples are mesa etched (H_3PO_4:H_2O_2:H_2O = 1:1:20) up to a depth of 1.5 μm. A small decrease (10%) of the threshold current density was found upon etching indicating that little current spreading[11] occurs. The lasers are individually tested using a probe needle and a standard photomultiplier detection system. For continuous-wave operation an Anritsu MS9001B optical spectrum analyzer is used.

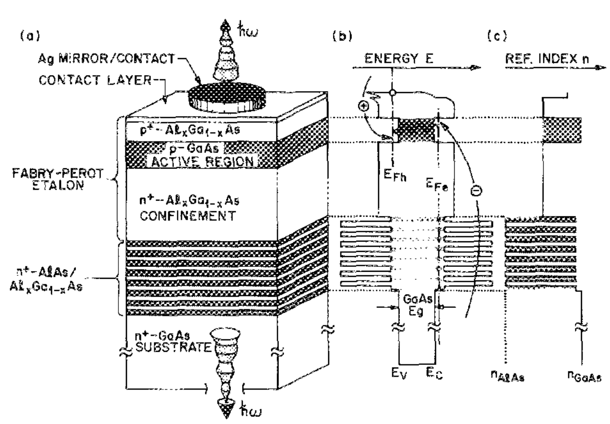

FIG. 1. Schematic (a) structure, (b) energy band diagram, and (c) refractive index profile of the metallic reflector vertical cavity injection laser (not to scale). A metallic (Ag) ohmic contact is used as a top reflector. The bottom reflector is a quarter-wave (λ/4) multilayer structure. Band bending in the λ/4 reflector region of the band diagram is neglected.

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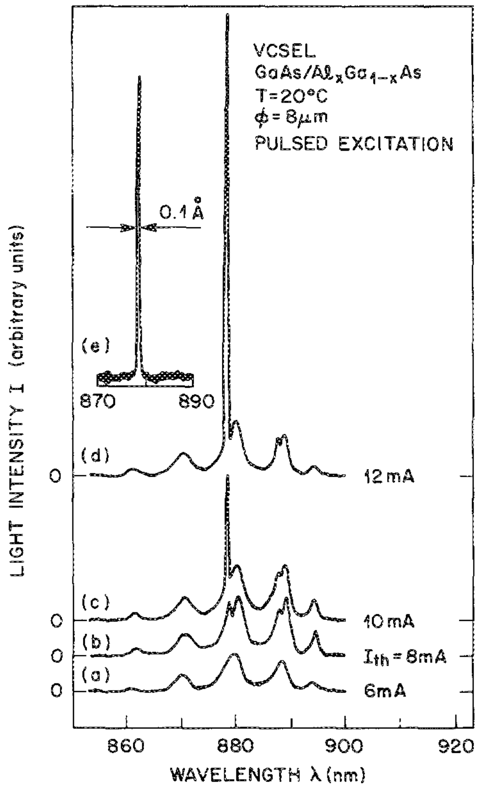

FIG. 2. Emission spectrum of a metallic reflector vertical cavity laser (a) below, (b) at, and (c),(d) above threshold. The contact diameter is 8 μm.

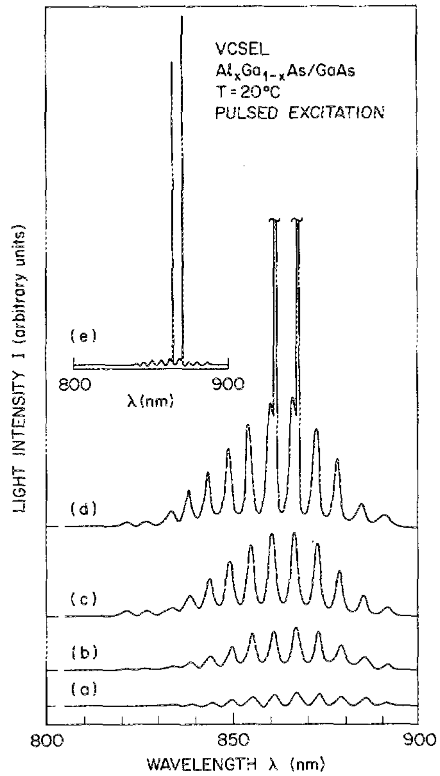

FIG. 3. Emission spectrum of a metallic reflector vertical cavity laser (a),(b),(c) below and (d),(e) above threshold. The Fabry–Perot cavity length is $\simeq 14$ μm.

The optical spectra of an 8-μm-diam GaAs VCSEL with a top Ag mirror are shown in Fig. 2 for currents (a) below threshold, (b) at threshold, and (c),(d) above threshold. The threshold current for laser emission is 8 mA which corresponds to a threshold current density of 16 kA/cm^2. For an 18-μm-diam laser a threshold current of 24 mA is measured which corresponds to a threshold current density of 9.5 kA/cm^2. The threshold current and the threshold current density are a remarkable improvement over previously reported results on GaAs VCSELs.[1] Single longitudinal mode emission occurs in the laser regime due to the short optical resonator of 4.1 μm. For such a cavity length the spacing of longitudinal modes is large resulting in single-mode emission. High-resolution spectra of the laser emission are measured with an 1800 grooves/mm grating in a 3/4 m spectrometer. The linewidth of the laser at threshold is <1 Å. At injection currents slightly above threshold, the linewidth decreases to 0.2 Å. Under optimized conditions a linewidth of 0.1 Å is measured. The value of 0.1 Å is limited by the resolution of the monochromator. The spontaneous emission spectrum reveals five Fabry–Perot resonances with an approximate separation of 100 Å.

A larger number of Fabry–Perot resonances are obtained in longer resonators as shown in Fig. 3. The thickness of the confining layers and the active region is 14.1 μm. The pronounced oscillatory characteristic of the spontaneous emission spectrum is indicative of low losses in the cavity and of the high quality molecular beam epitaxially grown GaAs and $Al_xGa_{1-x}As$. The finesse of the cavity as inferred from the linewidth and the line separation is 3.5. The finesse is determined by the bottom quater-wave mirror ($R_1 \cong 99\%$) and the top semiconductor-air interface ($R_2 \cong 32\%$). The calculated finesse of the two reflectors has a value of $F = \pi\sqrt{R}/(1-R) \cong 5.3$, where $R = \sqrt{R_1 R_2} = 0.56$. At higher injection intensities the laser

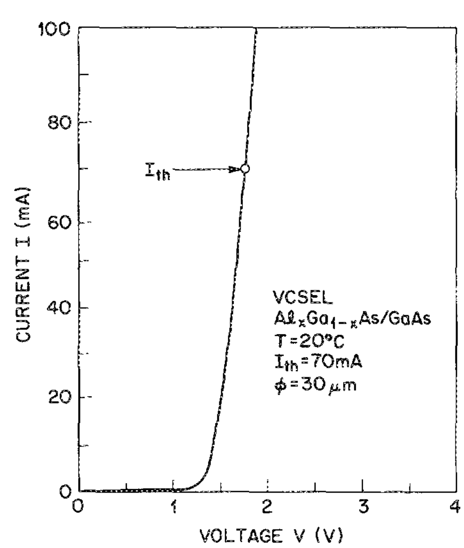

FIG. 4. Current-voltage characteristic of a metallic reflector vertical cavity laser with contact diameter of 30 μm. The differential resistance at threshold is 4.1 Ω. The voltage drop across the diode laser at threshold is 1.8 V.

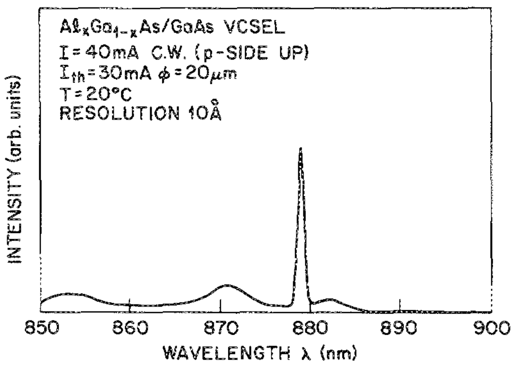

FIG. 5. Continuous-wave room-temperature laser spectrum of a metallic reflector vertical cavity $GaAs/Al_xGa_{1-x}As$ laser emitting at $\lambda = 879$ nm. The laser is mounted p side up with no special cooling techniques.

emits two longitudinal modes with wavelengths $\lambda = 862$ and 864 nm. The bimodal emission is due to the small resonance mode spacing such that both modes have sufficient gain for lasing.

The metallic reflector vertical cavity laser has excellent electrical characteristics due to the low series resistance on the p side (top) of the structure. The current-voltage characteristic of a 30-μm-diam vertical cavity laser is shown in Fig. 4. The turn-on voltage is ~ 1.3 V, i.e., a few kT lower than the GaAs band-gap energy. The voltage drop across the diode at lasing threshold is 1.8 V which is the lowest value reported for vertical cavity lasers. The differential resistance at the threshold current is 4.1 Ω. A low series resistance is essential for a large external power efficiency of the laser. The power efficiency of a laser coincides with the external quantum efficiency, if the voltage drop at the diode equals the photon energy, i.e., $\eta_{power} = \eta_{ext}$. However, if an additional series resistance R increases the voltage drop across the laser device, the power efficiency decreases by $\eta_{power} = (\eta_{ext}^{-1} + RI^2/P_{opt})^{-1}$, where η_{ext} is the external quantum efficiency and P_{opt} is the optical output power of the laser. Inspection of the equation reveals that a small series resistance R is essential for a high external power efficiency of the laser. For smaller contact diameters ($\phi = 15\,\mu$m) the diode voltage at lasing threshold remains 1.8 V, that is, independent of the contact diameter.

Continuous wave (cw) room-temperature operation of the metallic reflector vertical cavity laser is achieved for the first time with our improved structure. The cw spectrum of a 20 μm-diam contact is shown in Fig. 5. The laser wafer is bonded with a conductive epoxy on a copper slab and contacted with a probe needle. The p side is up during the cw operation and the substrate is not thinned. No special cooling technique such as p-side down mounting is required to achieve lasing. The cw spectrum is measured with an Anritsu optical spectrum analyzer. The resolution of the analyzer is chosen to be 10 Å for improved detection of the signal. The width of the laser line is resolution limited.

In conclusion, we report on a metallic reflector vertical cavity injection laser. The laser operates in the continuous wave mode at $T = 300$ K with threshold currents of 8 mA ($\phi = 8\,\mu$m) and threshold current densities of 9.5 kA/cm^2 ($\phi = 18\,\mu$m). Single longitudinal mode ($\Delta\lambda = 0.1$ Å) and bimodal operation are obtained in lasers with short and long Fabry–Perot étalons, respectively. A low series resistance (4.1 Ω) and a low diode voltage (1.8 V) at lasing threshold are characteristics of the metallic reflector structure. The results demonstrate that the metallic reflector structure is a promising structure for vertical cavity surface-emitting lasers.

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[1] D. G. Deppe, A. Y. Cho, K. F. Huang, R. J. Fischer, K. Tai, E. F. Schubert, and J. F. Chen, J. Appl. Phys. **66**, 5629 (1989).

[2] H. Soda, K. Iga, C. Kitahara, and Y. Suematsu, Jpn. J. Appl. Phys. **18**, 2329 (1979).

[3] L. Yang, M. C. Wu, K. Tai, T. Tanbun-Ek, and R. A. Logan, Appl. Phys. Lett. **56**, 889 (1990).

[4] J. L. Jewell, K. F. Huang, K. Tai, Y. H. Lee, R. J. Fischer, S. L. McCall, and A. Y. Cho, Appl. Phys. Lett. **55**, 424 (1989).

[5] A. Scherer, J. L. Jewell, Y. H. Lee, J. P. Harbison, and L. T. Florez, Appl. Phys. Lett. **55**, 2724 (1989).

[6] F. Koyama, S. Kinoshita, and K. Iga, Appl. Phys. Lett. **55**, 221 (1989).

[7] L. M. Zinkiewicz, T. J. Roth, L. J. Mawst, D. Tran, and D. Botez, Appl. Phys. Lett. **54**, 1959 (1989).

[8] P. L. Gourley, T. M. Brennan, B. E. Hammons, S. W. Corzine, R. S. Geels, R. H. Yan, J. W. Scott, and L. A. Coldren, Appl. Phys. Lett. **54**, 1209 (1989).

[9] R. J. Fischer, K. Tai, K. F. Huang, D. Deppe, and A. Y. Cho (unpublished); see also K. Tai, R. J. Fischer, C. W. Seabury, N. A. Olsson, T. C. D. Huo, Y. Ota, and A. Y. Cho, Appl. Phys. Lett. **55**, 2473 (1989).

[10] E. F. Schubert, J. E. Cunningham, W. T. Tsang, and T. H. Chiu, Appl. Phys. Lett. **49**, 292 (1986).

[11] N. K. Dutta, J. Appl. Phys. (to be published).