Transparent conductive metal-oxide contacts in vertical-injection top-emitting quantum well lasers

Li-Wei Tu, E. Fred Schubert, Hank M. O'Bryan, Yeong-Her Wang, Bonnie E. Weir, George J. Zydzik, and Alfred Y. Cho
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

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Optically transparent and electrically conductive cadmium tin oxide is employed in vertical cavity surface-emitting lasers for vertical current injection. Continuous wave lasing at room temperature is achieved in GaAs/AlGaAs quantum well lasers. Devices with a 10 μm optical window, which also serves as a vertical current injection inlet, give lasing threshold currents as low as 3.8 mA. The differential series resistance is 350–450 Ω with a diode voltage of 5.1–5.6 V at lasing threshold. Far-field pattern of the laser emission is Gaussian-like with a full width at half maximum of 7°.

There is much interest in vertical cavity surface-emitting lasers (VCSELs) in recent years, because of their planar structure, micro size, and single fundamental mode operation.[1] Due to the vertical cavity property of the lasers, the optical path aligns with the route of the injection current. This makes the designs of contacts and mirrors more complicated as compared to horizontal cavity lasers. For VCSELs using GaAs as the active material, side injection, which applies the current from the side of the optical path with either a ring contact/etched substrate[2] or a contacting pad/top emission,[3] is the major way that was used to overcome the obstacles. The vertical injection scheme, in which the current is injected directly through the top light-emitting window, e.g., using silver as both a mirror and a contact,[4–6] provides a way of simplifying the current contour, an effective pumping method, and a truly planar structure without the need of mesa formation. Other studies employing InGaAs as the active material and bottom emission through the substrate have also been reported.[7,8] This work uses GaAs as the active material and the vertical injection, top emission scheme. In this scheme, substrate etching is unnecessary,[2] and the injection current does not go through the ion-implanted region, which is damaged by the ion implantation, and has high resistance.[3]

Cadmium tin oxide (CTO) is optically transparent with a negligible absorption ($<1\%$) and electrically conductive with a conductivity of $2\times10^3\ \Omega^{-1}\,cm^{-1}$ at room temperature. It is applied in our laser structure on top of the top mirror to serve as the vertical-injection contact without blocking the light output. An intermediate layer of very thin silver films with thicknesses from 50 to 300 Å is used to facilitate the formation of the ohmic contact. Continuous wave (cw) operation at room temperature is achieved.

The GaAs/AlGaAs four quantum well structures are grown in a Riber molecular beam epitaxy system. Top *p*-type mirror is a 20-period, one-step graded semiconductor mirror,[9] which is to reduce the series resistance, with a structure of $Al_{0.14}Ga_{0.86}As$ (500 Å)/$Al_{0.57}Ga_{0.43}As$ (100 Å)/AlAs (580 Å)/$Al_{0.57}Ga_{0.43}As$ (100 Å). It is Be doped with a doping concentration of $5\times10^{18}\ cm^{-3}$ in the first 16 periods. Then, the concentration is increased to $2\times10^{19}\ cm^{-3}$ near the surface layer $Al_{0.14}Ga_{0.86}As$ (100 Å) to facilitate contacting. The active region is undoped, and consisted of four 100 Å GaAs quantum wells with 70 Å $Al_{0.3}Ga_{0.7}As$ barriers. The active region is cladded on the top and bottom by the confinement layers. The confinement layer is linearly graded $Al_xGa_{1-x}As$ with x graded from 0.3 to 0.57 near the mirrors with a thickness of 820 Å. This graded-index, separate-confinement heterostructure helps the carrier confinement, and reduces the lasing threshold current.[10] One-third of the confinement layer near the active region is undoped, and the rest is doped to $\sim1\times10^{18}\ cm^{-3}$. The *n*-type bottom mirror is a 29.5-period, one-step graded structure similar to the *p*-type mirror. It starts with 100 Å $Al_{0.57}Ga_{0.43}As$ from the substrate side and ends with 580 Å AlAs adjacent to the confinement layer. It is Si doped with a doping concentration of $1\times10^{18}\ cm^{-3}$. The substrates are heavily doped *n*-type (001) GaAs.

The laser structure is first examined with the reflectivity measurement using an Anritsu MS9001B optical spectrum analyzer. Fabry–Perot resonance shown as a clear dip in the stop band can be seen. Then, 300 keV protons in a dose of $1\times10^{15}\ cm^{-2}$ are implanted with the 10-μm-diam windows protected by a thick 6.2 μm photoresist. Before depositing 50–300 Å silver, a 1000 Å SiO_2 layer is grown at 100 °C in a high vacuum chamber by electron beam evaporation. The photoresist is stripped with acetone followed by plasma cleaning. The growth of CTO uses an rf magnetron sputtering system (Anelva Corp., Model SPF-332H). The target is a sintered disk (3 in. in diameter, 1/4 in. in thickness) with a nominal composition of Cd_2SnO_4 (Haselden, San Jose, California). The target is mounted 5 cm above the samples. The sputtering gas is a mixture of argon and oxygen at a total pressure of 23 mTorr. A deposition rate of 3 Å/s is maintained during coating. The resistivity of the CTO film depends strongly on the partial pressure of oxygen. For an oxygen partial pressure around 0.5 mTorr, the minimum resistivity is obtained. The CTO film thickness is $\sim$2000–4000 Å with negligible absorption (less than 1%, which is limited by the capability of the setup) at 0.85 μm. The resistivity is $\sim5\times10^{-4}\ \Omega$ cm. Hall measurements indicate that the CTO films are n type with a carrier concentration of $\sim1\times10^{20}\ cm^{-3}$ and a Hall mobility of $\sim100\ cm^2/V$ s at

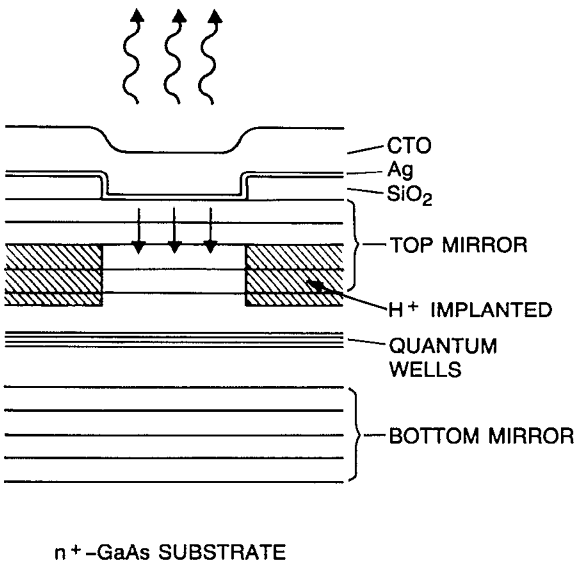

FIG. 1. Schematic diagram of a vertical-injection VCSEL. Current is vertically injected through the optical window as indicated by the arrows.

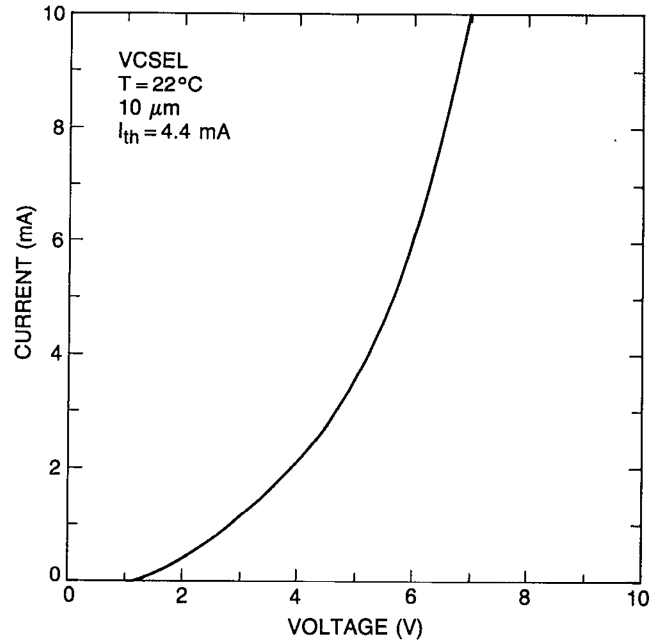

FIG. 3. Current vs voltage curve for the same device as in Fig. 2. The voltage at lasing is 5.4 V with a differential series resistance of 430 Ω.

room temperature. Standard buffered oxide etchant is used to etch the CTO layer in the process of device isolation.

Before the lasing properties are characterized, the substrate side of the sample is bonded with conductive epoxy on a copper slab which serves as a heat sink. No other cooling setup is used. All experiments are done at room temperature. Figure 1 is a schematic drawing of the device structure. A fine probe is used to electrically contact and pump the lasers. Current is vertically injected through the window area as shown with arrows in Fig. 1. The area of the device top surface other than the light emission window is electrically isolated with the SiO_2. The shaded area in Fig. 1 is the proton implantation region which helps the current confinement. Figure 2 is the cw light output power versus direct current. The light output power is measured with an ANDO AQ-1125 optical power meter calibrated at 0.85 μm. The lasing threshold current is 4.4 mA with ~10% external differential quantum efficiency at a lasing wavelength of ~0.85 μm. Threshold currents as low as 3.8 mA are obtained. The rollover of the lasing power at 6 mA is believed due to heating as indicated from pulsed (100 ns, 1 kHz) measurements which show light output power more than 2 mW at ~20 mA. The thin intermediate silver layer of 200 Å thickness in this sample causes a small reduction in the laser output power (about 20%). Figure 3 is the current-voltage curve which shows a voltage of 5.4 V and a differential series resistance of 430 Ω at the lasing threshold current of 4.4 mA (see Fig. 2).

Lasing spectra are measured and show a single longitudinal and single transverse mode with a linewidth of 0.2 Å. Figure 4 shows the far-field light intensity distribution measured at a detector-sample distance of 8.3 cm. The

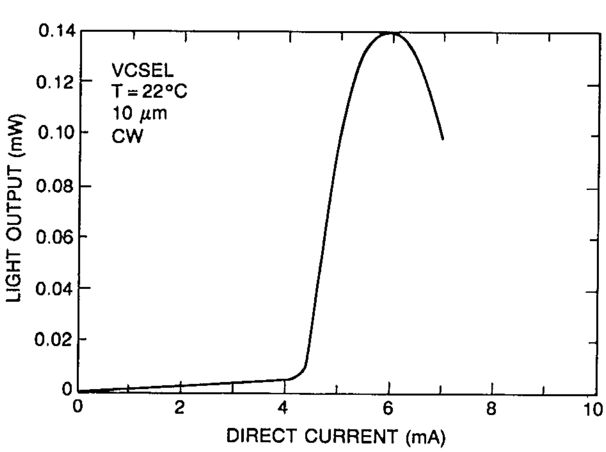

FIG. 2. Continuous wave light output power vs direct current at room temperature. The lasing threshold is 4.4 mA. The lasing wavelength is at ~0.85 μm.

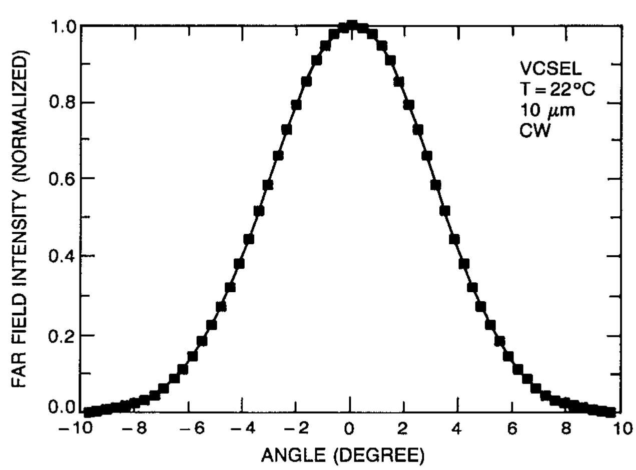

FIG. 4. Far-field light intensity distribution under continuous wave operation at 5 mA. It is Gaussian-like with a full width at half maximum of 7.0°. Data points are connected by straight lines. Normalized light intensity is shown.

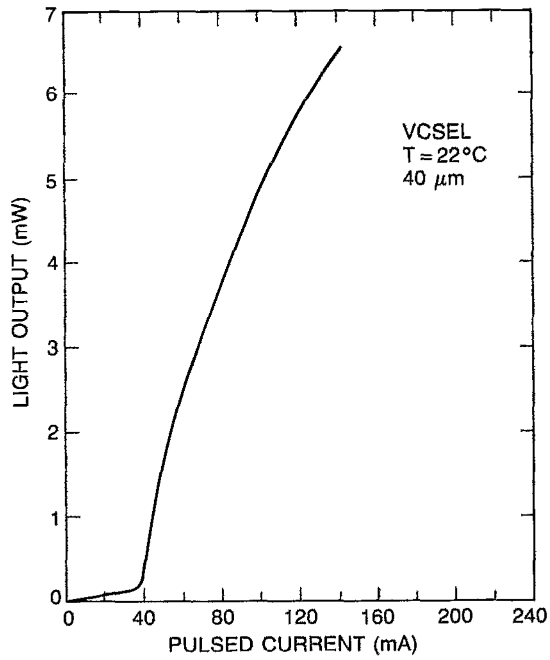

FIG. 5. Light vs current curve for a structure without ion implantation under 100 ns, 1 kHz pulsed current. The threshold current density is 3 kA/cm^2.

distribution is Gaussian-like, indicating a single fundamental transverse mode operation, with a full width at half maximum of 7.0°. Measurement is performed at a step of ~0.35°, with a resolution of better than 0.2°.

We also fabricate a structure without proton implantation. It is mesa etched, and probed directly at the top window area. A device with a 40-μm-diam mesa gives a pulsed (100 ns, 1 kHz) threshold current of 40 mA, which yields a threshold current density of 3 kA/cm^2 (see Fig. 5). More than 30% reduction in the light output power results from 300 Å Ag in this sample, and from the blocking by the probe itself. The light output power at 140 mA is 6.5 mW.

The Ag thin layers used in our structures are solely for forming ohmic contacts. Structures with thin Ag alone without thick CTO layers are unsuccessful. This may be ascribed to the *ex situ* growth of the very thin Ag layers, which have low perfection in the structure quality. Surface/interface scattering can increase the thin Ag film resistivity substantially.[11] Initial experiments on samples having reverse-type structures, which have bottom *p*-type mirrors, and top *n*-type mirrors, show good performances with CTO layers deposited right on the top of the heavily doped *n*-type mirrors as vertical-injection current contacts. Ag layers are unnecessary in these reverse-type structures.

In conclusion, a novel concept for vertical-injection VCSEL structures is demonstrated using optically transparent and electrically conductive CTO. This structure provides a solution to one of the fundamental difficulties in VCSELs, i.e., the light and current occupy the same path. Room-temperature continuous wave operation with low threshold current is achieved. The Gaussian-like far-field pattern indicates a single fundamental transverse mode.

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