sity profile should be independent of the size of the heating "area" for semi-infinite media. Similarly, one should obtain the same simulated response independent of the choice of the radius ω. In this regard, we note, for example, that the simulated response for 2.44 W, which is shown in Fig. 1, is also obtained with ω equal to ω_i or to ω_c. However, new values are obtained for B ($B \pm 2\%$, respectively, with B the value for $\omega = \omega_s$). We can eliminate those values of B outside the limits of experimental error for those values of ω greater than ω_c or less than ω_i and get a measure of the usefulness of this approximation. The measured value of B was determined[4] to be $10.7 \pm 25\%$ K cm^2/J. The values of B obtained by fitting are within this range (the best fit being obtained with $\omega = \omega_s$).

As Fig. 1 illustrates, it is generally found that the fit to the actual response is adequate, although there are times when it is poor, as shown for the case of 4.88 W. It is not clear yet whether this is due to a nonuniform phosphor coating or other factors.[1,2] In general, the simulated response is enveloped by the experimental response, which indicates that the temperature dependence of the thermal conductivities should be included in the comparison.[2]

We have extended the previous solution[1,2] of the diffusion equation to all times, albeit for a specially considered two-layer system, and we have illustrated its usefulness by applying it in the field of solid-state dosimetry. While we have considered a composite that was heated through the phosphor layer, the above analysis is readily extended to such a composite heated through the glass layer. It appears then that laser heating of practical dosimeter configurations consisting of phosphor-coated glass are adequately described by Eq. (1) above provided only that the glass is a much better absorber than the phosphor. The idea of using TL response to solve the diffusion equation is novel. It is limited in this instance by experimental error and, because of the large uncertainty in B, the present method is not a very sensitive test. Perhaps a better composite system can be found: one in which the temperature dependence of all the material parameters is known. Finally, we note, that the approximation used herein is probably valid for any shape of the heating "spot."

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AlGaAs-GaAs and AlGaAs-GaAs-InGaAs vertical cavity surface emitting lasers with Ag mirrors

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We describe vertical cavity surface emitting lasers of GaAs active regions (0.7 μm thick) emitting at 0.85 μm and of In$_{0.1}$Ga$_{0.9}$As-GaAs active regions emitting at 0.90 μm. The vertical cavity is formed using an Al$_x$Ga$_{1-x}$As-AlAs quarter-wave stack as the n-type mirror and the metal Ag as the p-type mirror. The Ag mirror has potential for reduced series resistance, reduced thermal resistance, and more simplified device processing over other mirror structures for vertical cavity laser diodes. Current thresholds for pulsed room-temperature operation as low as 16 kA/cm^2 for the GaAs and 51 kA/cm^2 for the In$_{0.1}$Ga$_{0.9}$As-GaAs devices have been measured.

There is growing interest in vertical cavity surface emitting (VCSE) semiconductor lasers[1-3] because of several advantages they may offer over the more common edge emitting or lateral cavity surface emitting lasers. In the vertical cavity laser, quarter-wave stacks of index differing semiconductor layers can be monolithically integrated into the laser structure providing in some cases both high reflectivity and good electrical conductivity.[4-7] The short cavity length inherent in the VCSE laser can result in stable single-mode laser operation.

Because of the extremely short gain path in the VCSE laser, a much smaller active volume is possible as compared to the lateral cavity lasers. For example, for a 2-μm-diam VCSE laser, dimensions achievable using standard photolithography and sophisticated device processing, for a threshold current density of 10^4 A/cm^2 the device would have a threshold of <0.5 mA. Also, larger symmetrical optical

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emitter apertures should result in improved far field radiation patterns over that of conventional edge emitters. These properties, improved optical characteristics, method of mirror formation, and the potential for low-threshold operation, make the VCSE laser very desirable for opto-electronic integrated circuits, optical fiber interconnects, and two-dimensional laser arrays.

To date, however, the development of the vertical cavity laser has been limited by high current thresholds which place a stringent demand on heat sinking. Continuous-wave room-temperature operation has only recently been achieved[8] using special heat sinking techniques. For mirror formation in the GaAs-AlAs crystal system, quarter-wave mirrors of n-type material, which are both highly reflecting and low resistance, can be epitaxially fabricated. However, the p-type semiconducting quarter-wave mirror presents several problems to the VCSE laser in terms of electrical conductivity, thermal resistance, and device fabrication.

In this communication we present an alternative method for the p-side mirror formation which utilizes the metal Ag as both the mirror and p-side electrical contact. The Ag mirror offers the potential for reduced series resistance, reduced thermal resistance, and more simplified device processing over a quarter-wave semiconductor layered structure. From optical data on Ag,[9] reflectivity $\gtrsim 0.97$ should be possible for wavelengths of ~ 0.88 μm. Here we show that Ag is a suitable reflector for both GaAs-Al$_x$Ga$_{1-x}$As surface emitting laser structures emitting at $\lambda \sim 0.85$ μm and also strained-layer In$_{0.1}$Ga$_{0.9}$As-GaAs-Al$_x$Ga$_{1-x}$As structures emitting at $\lambda \sim 0.90$–0.91 μm. The longer wavelength possible with the In$_{0.1}$Ga$_{0.9}$As-GaAs structures are of importance because of the transparency of the GaAs substrate at these wavelengths ($\alpha_L \sim 10$ cm^{-1} for n^+ GaAs[10]) which simplifies coupling the device to an optical fiber.

Figure 1 illustrates the device structures used in this study. The crystals have been grown using molecular beam epitaxy. The first structure consists of an n-type ($n_{Si} \sim 5 \times 10^{17}$ cm^{-3}) AlAs-Al$_{0.1}$Ga$_{0.9}$As quarter-wave stack consisting of 23 pairs followed by an Al$_{0.3}$Ga$_{0.7}$As ($n_{Si} \sim 5 \times 10^{17}$ cm^{-3}) lower confining layer of thickness ~ 0.5 μm, a p-type GaAs active region ($n_{Be} \sim 5 \times 10^{16}$ cm^{-3}

of thickness ~ 0.7 μm, an Al$_{0.3}$Ga$_{0.7}$As upper p-type confining layer ($n_{Be} \sim 5 \times 10^{16}$ cm^{-3}) of thickness ~ 0.4 μm, and a p^+ GaAs layer (n_{Be} 5×10^{18} cm^{-3}) of thickness ~ 0.01 μm for contacting purpose. The strained layer structure for longer wavelength is nearly identical except for the n-type quarter-wave mirror which uses GaAs for the high-index material as opposed to Al$_{0.1}$Ga$_{0.9}$As, and the active region which consists of 0.1 μm of n-type GaAs followed by 50 pairs of In$_{0.1}$Ga$_{0.9}$As quantum wells (QWs) of thickness 80 Å with barrier layers of GaAs of thickness 150 Å, all p-type ($n_{Be} \sim 10^{17}$cm^{-3}), followed by 0.1 μm of p-type GaAs ($n_{Be} \sim 10^{18}$cm^{-3}). The upper and lower Al$_{0.3}$Ga$_{0.7}$As confining layers and p^+ GaAs contact layer are identical in both structures. Crosshatch is observed on the wafer with In$_{0.1}$Ga$_{0.9}$As QWs indicating some dislocations are present in the structure's active region.

Both the p-side mirror and electrical contact are formed simultaneously by defining a 15- or 30-μm-diam dot of 0.55-μm-thick Ag on the p^+ GaAs using thermal evaporation and photoresist lift off. Although the Ag-GaAs mirror forms a nonalloyed contact, the current-voltage characteristics are found to be quite linear above "turn-on" (~ 1.2 V) with forward series resistances of 10–15 Ω for the 15-μm-diam contact. The devices are tested in a p-side up configuration under pulsed current excitation by measuring the characteristics of the light output emitted around the Ag contact as shown in Fig. 1. We note that although for device operation a more favorable configuration is with the p-GaAs/Ag side mounted on a heat sink and a semitransparent mirror on the n-side as demonstrated by others,[1,11] the p-side up configuration allows rapid testing of many devices through the use of a movable probe.

Figure 2 shows the room-temperature spectral characteristics of the VCSE with a GaAs active region and a 30-μm-diam Ag mirror/contact. Even at very low currents the
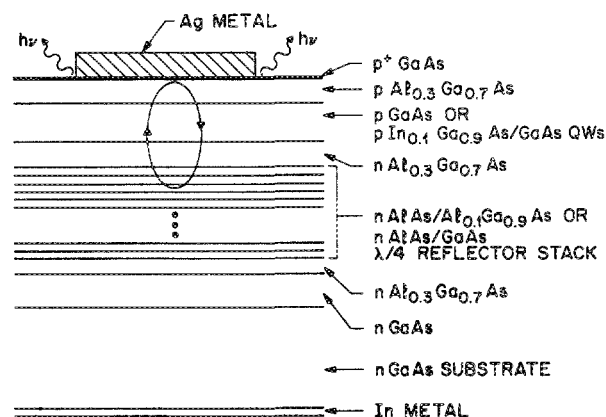

FIG. 1. Illustration showing the vertical cavity surface emitting laser utilizing an n-type Al$_x$Ga$_{1-x}$As-AlAs quarter-wave stack for the n-type mirror and Ag for the p-type mirror.
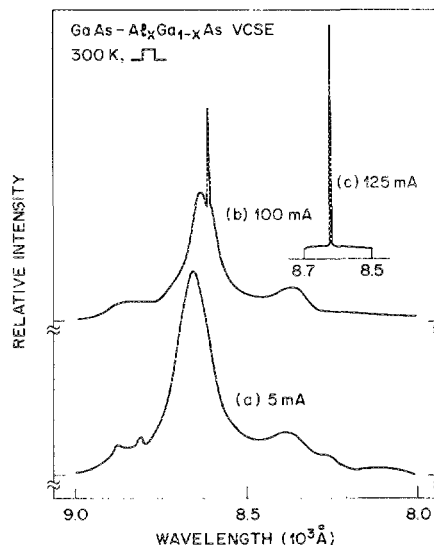

FIG. 2. Room-temperature spectral characteristics of a vertical cavity surface emitting laser with a 0.7-μm-thick GaAs active region. The diameter of the Ag mirror/contact is 30 μm.

measured spontaneous spectrum is shifted to high energies at $\lambda \sim 0.86\,\mu m$, suggesting that the lower n-type distributed Bragg mirror is centered at a slightly shorter than optimum wavelength. At a pulsed current of 100 mA a lasing mode is observed in the light spectrum which at only slightly higher current, 125 mA, dominates the spectrum. The spectral width of the lasing mode is less than 1 Å. Threshold currents measured on several devices of 30 μm diameter typically ranged from 100–125 mA. Not all the devices tested lased but instead showed Fabry–Perot modes of 4–5 Å width above certain current levels, which remained comparable in intensity to the background spontaneous light.

Figure 3 shows the emission spectrum of a 15-μm-diam device fabricated on the wafer with the $In_{0.1}Ga_{0.9}As$-GaAs QW active region. In this case the $In_{0.1}Ga_{0.9}As$ QWs shift the laser emission to 0.91-μm wavelength.

Figure 4 shows the light versus current curve measured for a 15-μm device with the $In_{0.1}Ga_{0.9}As$-GaAs QW active region. The threshold current can be seen to be ~ 90 mA, or a current density of ~ 51 kA/cm^2. Threshold current densities of 30 μm devices are typically between 400–450 mA.

As mentioned earlier, compared to semiconductor quarter-wave stacks for the p mirror,[11] the Ag mirror offers many advantages. The p-type quarter-wave layers of $Al_xGa_{1-x}As$-$Al_{x'}Ga_{1-x'}As$ for $x \sim 0$ and $x' \sim 1$ can contribute significant series resistance to the VCSE laser, an effect apparently related to the p-type heterojunctions. At the same time a major contribution to the device's thermal resistance is again the p-type confining layers. The increased electrical resistance means increased heat generation while the increased thermal resistance of the p-type layers impedes heat flow out of the crystal. Although less severe, other forms of nonconducting p-type mirrors also limit the p-type
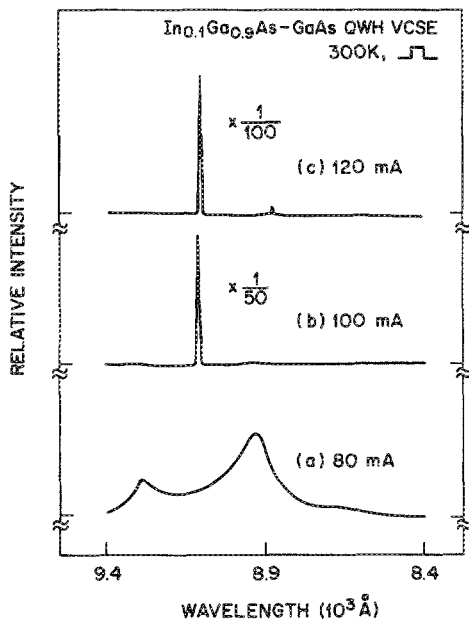

FIG. 4. Room-temperature light vs current characteristics of a 15-μm-diam $In_{0.1}Ga_{0.9}As$-GaAs vertical cavity surface emitting laser under pulsed current excitation.

confining layer thickness since they must rely on current spreading under the mirror to excite the active region.[6] This thickness limitation of the p-type confining layer is greatly reduced with the Ag mirror, while the Ag also provides excellent thermal conductivity.

In summary, we have shown that the metal Ag can form a suitable mirror for VCSE lasers. Using a semiconductor quarter-wave stack for the n-type mirror and a 0.55-μm-thick Ag layer for the p-type mirror, threshold current densities of ~ 16 kA/cm^2 have been achieved. The Ag mirror is expected to offer advantages in heat sinking through reduction of the upper p-type confining layer thickness, and also simplify device fabrication for more complex smaller diameter VCSE laser structures. We have also demonstrated VCSE laser with $In_{0.1}Ga_{0.9}As$ QW active regions emitting at $\lambda_L \sim 0.90\,\mu m$. This longer wavelength is of special interest because of the transparency of the GaAs substrate.

FIG. 3. Room-temperature spectral characteristics of a vertical cavity surface emitting laser with an active region of 50 quantum wells of $In_{0.1}Ga_{0.9}As$ separated by GaAs barriers. The diameter of the Ag mirror/contact is 15 μm.
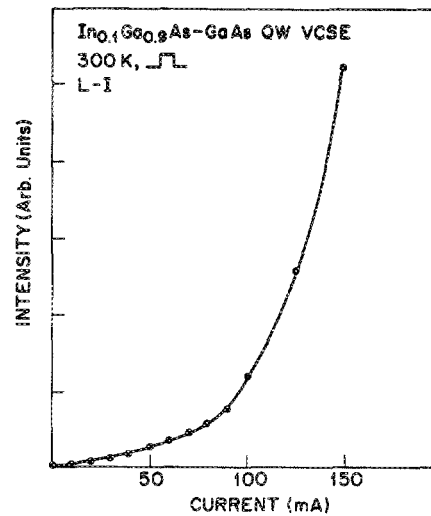
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