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Low series resistance vertical-cavity front-surface-emitting laser diode

Hoi-Jun Yoo,[a] J. R. Hayes, N. Andreadakis, E. G. Paek, G. K. Chang,
J. P. Harbison, and L. T. Florez
Bellcore, Red Bank, New Jersey 07701-7040

Young-Se Kwon
Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Cheongryang, P. O. Box 150, Seoul, Korea

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We have fabricated a front-surface-emitting laser diode (FSELD) using a technique which relies on a double ion implant of oxygen and beryllium. The laser had a low operating voltage at the lasing threshold, a low series resistance, and a relatively small threshold current of 6 mA for a 25-μm-diam device. The lasing wavelength was 971 nm and the spectral width above threshold was 5 Å. Since the light comes from the front surface of the wafer, the fabrication technique described here for realizing a FSELD can be used for the fabrication of vertical-cavity visible surface-emitting lasers.

Vertical-cavity surface-emitting lasers are of interest for various applications[1–3] (e.g., parallel signal processing, high-speed optical interconnects, and two-dimensional phase-locked arrays) because it is possible to fabricate densely packed laser arrays without resorting to the difficult processing steps for optical output coupling perpendicular to the wafer. Moreover, it has a circular, narrow beam that shows dynamic single-mode operation over a wide temperature range.[1] Recently, there have been several reports of low threshold current operation using vertical-cavity surface-emitting laser diodes comprising high reflectance mirrors and tight current confinement to reduce the threshold current.[4–7] However, most research has focused on the 0.87 μm wavelength region, a wavelength at which light is absorbed in the GaAs substrate. The absorption problem can be overcome by etching a Via hole. However, the complication of front-to-back mask alignment and careful etching process must be employed.[1,4,5] In order to overcome this difficulty, InGaAs strained quantum wells ($\lambda_g = 0.98\,\mu$m) have been successfully used for the fabrication of vertical-cavity surface-emitting lasers.[6] However, the semiconductor stacked layers forming the high reflectance mirror, which have been used by Jewell *et al.*[7], caused the problem of a large series resistance leading to higher power consumption above threshold, in spite of the low laser threshold current. Also, the large step height of the mesa forming the laser makes it difficult to integrate this device with other electronic and/or optoelectronic devices. In addition, the active layer is exposed to air which levels to a large nonradiative surface recombination current.

In order to solve these problems, we fabricated a front-surface-emitting laser diode (FSELD) based on a double ion implantation technique, which emits light from the front surface rather than through the substrate. In addition to low series resistance and less absorption, the FSELD shows many advantages over the conventional vertical-cavity surface-emitting lasers. Since it has a planar structure and its fabrication process is exactly the same as that of high-speed heterojunction bipolar transistors,[8] optoelectronic integrated circuits comprising FSELDs should be easy to realize and have the potential for large scale integration. Since the light emerges from the front surface, the limitation in emission wavelength which comes from the substrate absorption is removed making this technology attractive for the fabrication of various emission wavelength SELDs, such as a visible laser. Also, since the active layer is surrounded by a semi-insulating layer, the current is tightly confined to the active region and there is no nonradiative current resulting from surface recombination that would lead to a higher threshold current.

A schematic diagram outlining the fabrication process of the FSELD is shown in Fig. 1. The FSELD comprised AlAs/GaAs bottom distributed Bragg reflector (DBR) layers, an AlGaAs lower cavity layer, an InGaAs strained quantum well active layer, an AlGaAs capping layer, and AlAs/GaAs top DBR layers grown on an n^+-GaAs substrate by molecular beam epitaxy. Actually, the top DBR is not essential for the fabrication of the FSELD since we intend to use a Si/Al$_2$O$_3$ dielectric stack for the top mirror, but was included for the subsequent fabrication of a mesa-etched surface-emitting laser for the purpose of comparison. A part of the wafer was processed to make mesa-etched surface-emitting lasers. The remaining section of the wafer had the

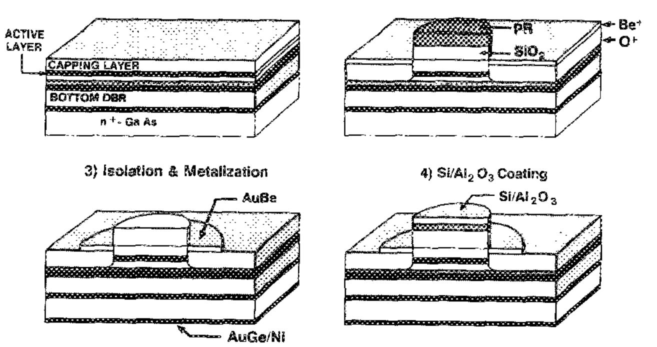

FIG. 1. Schematic diagram illustrating the fabrication steps of the FSELD using the double ion implantation technique.

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[a] On leave from Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Seoul, Korea.

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top mirror removed by ion beam milling and wet chemical etching to a point close to the AlGaAs capping layer. Therefore, only the bottom DBR remains, in contrast to a conventional InGaAs active layer surface-emitting laser. Since the current flows through only one DBR mirror, which is the electron injector, a low series resistance diode can be obtained.

To fabricate the FSELD a thick SiO_2 layer was deposited on the etched surface and patterned to form 25-μm-diam dots. The photoresist and SiO_2 disk were then used as an ion implantation mask for the O^+ implant to form a high-resistivity layer around the active region. This prevents current leakage through the extrinsic layer under the *p* electrode and confines the injected current to the intrinsic active layer under the dielectric DBR. A subsequent Be^+ implant was then carried out with the same mask in place to make a good ohmic contact to the extrinsic active region on the semi-insulating layer. The sample was then encapsulated in Si_3N_4 and annealed in a flowing argon atmosphere for 20 s at 850 °C.

Following the anneal, AuBe was evaporated onto the Be-implanted surface using standard electron beam evaporation and lift-off techniques. The *p* electrode was deposited around the SiO_2 dot that had a ring shape with an inner diameter of 25 μm and an outer diameter of 65 μm. After alloying, the remaining Be-implanted area was etched away using wet chemical etching to obtain device isolation. The top DBR was made of an electron beam evaporated Si/Al_2O_3 stack on top of the SiO_2 and patterned using standard lift-off techniques. The backside of the wafer was lapped to $\sim$100 μm thickness and mirror polished with a 2% Br_2-MeOH solution. Since the light will emit from the front surface, a thick AuGe layer, $\sim$0.5 μm, was coated on the backside to enhance the thermal dissipation. A micrograph of a FSELD, fabricated using the double ion implantation techniques described above, is shown in Fig. 2.

The forward current/voltage characteristics of the FSELD and mesa-etched SELD of the same diameter, are shown in Fig. 3. As can be clearly seen in Fig. 3, the FSELD shows a current-voltage characteristic that has significantly less series resistance than the mesa-etched SELD. For example, at an operating current of 4 mA the FSELD has a voltage drop of 3 V compared to 8 V for the mesa-etched SELD. As can be seen, the addition of a good ohmic contact and one DBR leads to a significant reduction in the bias voltage at threshold. The significant reduction in operating voltage results from the absence of the high-resistance *p*-doped mirror that was also required to function as the hole injector.

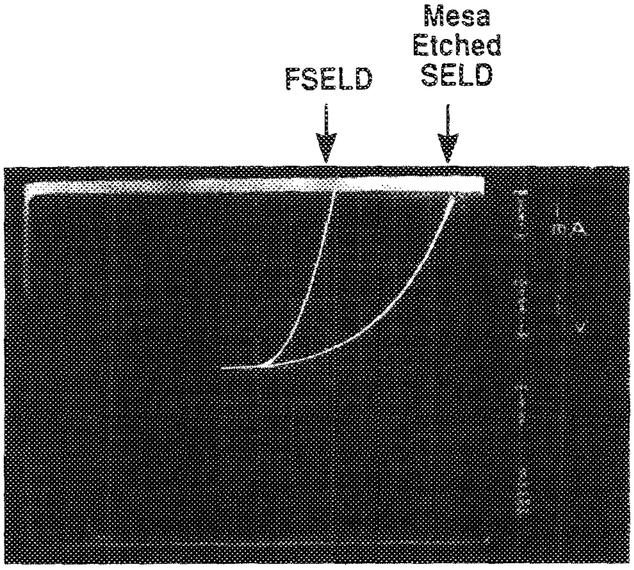

FIG. 3. Current-voltage characteristics of a FSELD and a mesa-etched SELD having the same diameter of 25 μm.

The lasing characteristics of FSELDs were evaluated at room temperature using 400 ns pulses operating at a 5 kHz repetition rate. The measured light-current characteristics are shown in Fig. 4. A typical threshold current for a 25-μm-diam FSELD is 6 mA, which is comparable to the lowest reported threshold current for any SELD. In comparison the mesa-etched SELD, also having a 25 μm diameter, fabricated from the same wafer shows a typical threshold current of 15 mA. We believe that the low threshold current of the FSELD is due to the tight current confinement in the active region, resulting from the O^+-implanted semi-insulating re-

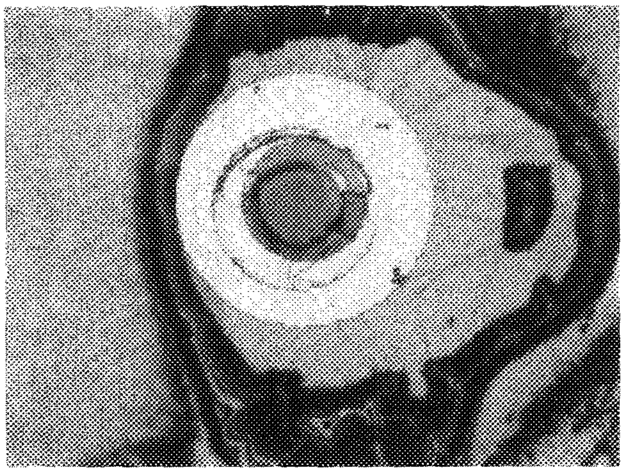

FIG. 2. Microphotograph of the fabricated FSELD.

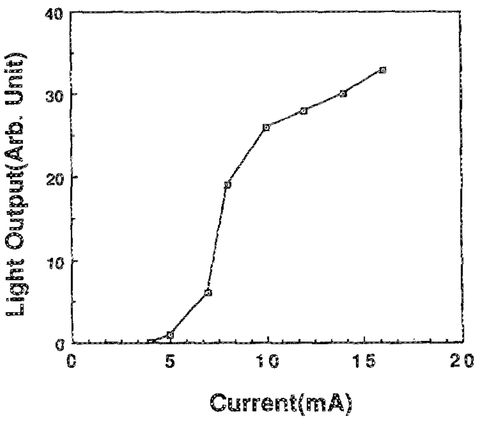

FIG. 4. Light output and current characteristics of the FSELD under pulsed operation.

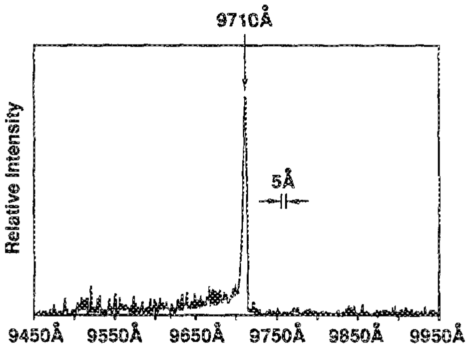

FIG. 5. Wavelength spectrum of the FSELD above the lasing threshold (the full width at half maximum was 5 Å).

gion. The spectrum of a typical FSELD above threshold is shown in Fig. 5. The lasing wavelength is 971 nm and spectral linewidth, above threshold, is about 5 Å. For a range of currents up to several times the threshold current, only single-mode operation is observed because the mode spacing is much larger due to its short cavity length.

In conclusion, we have fabricated a FSELD using a double ion implantation of oxygen and beryllium. The structure was found to have a low series resistance resulting from the low *p*-contact resistance and use of one DBR layer, and a low threshold current of 6 mA resulting from both a tight confinement of current in the active region and minimal surface leakage. The 25-μm-diam FSELD had a lasing wavelength of 971 nm and a spectral linewidth of 5 Å. Since there is no limitation in emission wavelength which comes from the substrate absorption, the FSELD can be used to fabricate various emission wavelength SELD, such as visible SELD.

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