Metal–Mirror-Based Resonant-Cavity Enhanced Light-Emitting Diodes by the Use of a Tunnel Diode Contact

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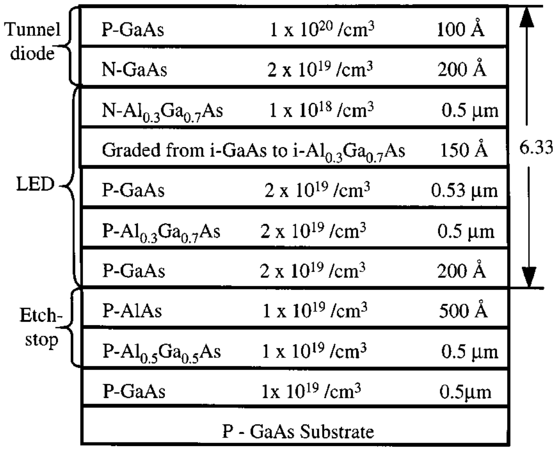
***Abstract*—We, for the first time, designed and fabricated resonant-cavity light-emitting diodes for high-speed optical communications using a tunnel diode contact scheme. Use of a tunnel diode provides extra freedom in designing the device contact and cavity mirror, which allows the realization of a resonant cavity without requiring distributed Bragg reflectors. The fabricated resonant-cavity light-emitting diodes have half the spectrum bandwidth and nearly triple the fiber-coupled power of noncavity devices.**

***Index Terms*—Light-emitting diode, optical communications, resonant cavity, tunnel diode.**

I. INTRODUCTION

A RESONANT cavity improves the emission characteristics of a light-emitting diode (LED) by reducing its spectral linewidth while increasing its emission power and directionality. The resonant-cavity light-emitting diode (RCLED) is a promising low-cost light source for fiber-optic communications [1], [2]. Limited by the device growth and processing techniques, the mirrors of choice for most RCLEDs are still distributed Bragg reflectors (DBRs) of multiple pairs [1]–[5]. The design and growth of a DBR significantly increases the cost of these devices. What is more important, some material systems do not have compatible semiconductor DBRs, which makes it very difficult to fabricate RCLEDs [6]. It is highly desirable to develop techniques to integrate low-cost mirrors (e.g., metal mirrors) with active LED materials, thus reducing the cost of RCLEDs.

For a RCLED using all metal mirrors, its metal layers should serve not only as good current-conducting paths to the LED active region, but also as high-reflectivity mirrors. Unfortunately, the typical metal contacts for semiconductor materials usually are not good reflectors. This is especially true when annealing is required to achieve ohmic behavior, which induces a rough semiconductor/metal interface. Since the necessitation of contact annealing usually depends on the doping type of the semiconductors, one way to avoid alloyed contact is to alter the doping type of the terminating semiconductor surface. For example, n-GaAs needs an alloyed contact while p-GaAs does not. A tunnel diode is the perfect structure to change the doping type of a terminating surface without degrading the device performance. The tunnel diode is a p-n junction device with heavily doped p- and n-regions, which exhibits nearly linear current versus voltage (I–V) behavior under small bias. It provides a smooth surface for mirror/contact metal attachment.



Tunnel diode	P-GaAs	1 x 10^{20} /cm^3	100 Å
	N-GaAs	2 x 10^{19} /cm^3	200 Å
LED	N-$Al_{0.3}Ga_{0.7}As$	1 x 10^{18} /cm^3	0.5 μm
	Graded from i-GaAs to i-$Al_{0.3}Ga_{0.7}As$		150 Å
	P-GaAs	2 x 10^{19} /cm^3	0.53 μm
	P-$Al_{0.3}Ga_{0.7}As$	2 x 10^{19} /cm^3	0.5 μm
	P-GaAs	2 x 10^{19} /cm^3	200 Å
Etch-stop	P-AlAs	1 x 10^{19} /cm^3	500 Å
	P-$Al_{0.5}Ga_{0.5}As$	1 x 10^{19} /cm^3	0.5 μm
	P-GaAs	1x 10^{19} /cm^3	0.5μm
	P - GaAs Substrate		

Fig. 1. Structure of a RCLED with tunnel diode scheme ($\lambda = 890$ nm in the air).

Previously, we have reported the material design and growth of GaAs–AlGaAs nonresonant-cavity LEDs with the highest frequency response to date [7]. In this letter, we report the design and fabrication of RCLEDs with the same high-speed materials. To our knowledge, this is the first report on incorporating a tunnel diode scheme into the RCLED structure. The use of a tunnel diode and simple yet reliable substrate-removal technique allows us to achieve RCLEDs consisting of only metal mirrors. By eliminating the DBR, we could significantly decrease the cost of the epitaxial growth for high-speed RCLEDs.

II. DEVICE DESIGN AND PROCESSING

The structure of our high-speed RCLED with tunnel diode contact scheme is illustrated in Fig. 1. The LED active layer was heavily doped (2×10^{19}/cm^3), which ensures a minimum 3-dB electrical bandwidth of 440 MHz. Potentially, the bandwidth may be further improved to the gigahertz range by increasing the doping concentration up to 7×10^{19}/cm^3 [7]. In this letter, we incorporated a tunnel diode on top of the LED heterojunction. Here, the tunnel diode changes the original terminating n-GaAs surface to a p-type GaAs surface. Instead of using Au–Ge–Ni or Au–Zn alloyed system, we used Ag for the LED n-side ohmic

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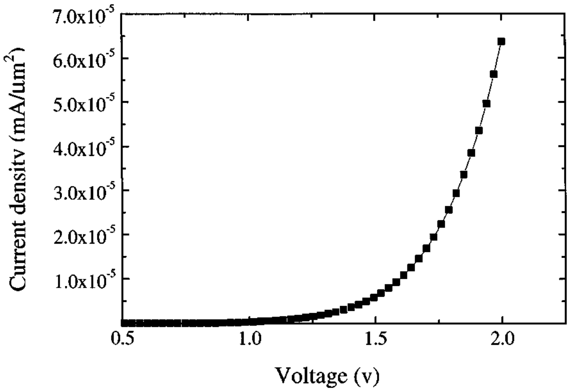

Fig. 2. I–V characteristics of the RCLEDs.

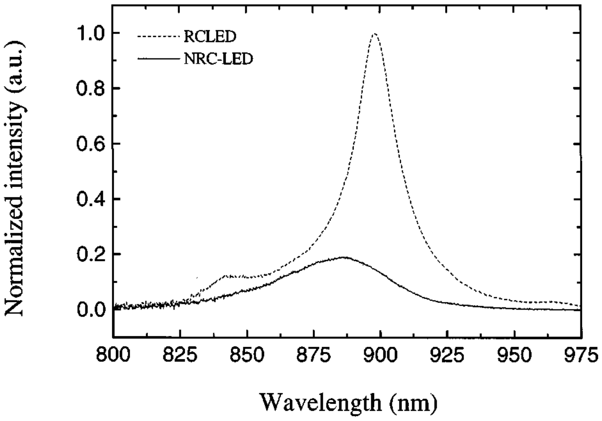

Fig. 3. Optical emission spectra of the RCLEDs and nonresonant-cavity LEDs at pump current of 4 mA.

contact in our RCLED. The smooth Ag–GaAs interface also acts as a high-reflectivity mirror ($R \approx 94\%$ estimated from theory). Note that the usage of a tunnel diode is not limited to the GaAs system for nonalloyed contacts. It also finds applications in any other material system requiring the alteration of surface doping type.

The RCLED was grown in a Varian Gen II MBE system. The tunnel diode layers were grown at 450 °C. Under these conditions, tunnel diodes have demonstrated good temperature stability and a nearly linear I–V curve under reverse bias with a specific contact resistance of about 9×10^{-5} Ω·cm^2 [8]. We optimized the overall thickness of the RCLED cavity medium to 6.33λ. This includes both LED heterojunction and the tunnel diode, and takes into account the phase shift at the two Ag metal-mirrors at both ends of the cavity. Here, $\lambda = 890$ nm in air, which is the emission center wavelength of the LED active materials (GaAs, $\mathrm{p} = 2 \times 10^{19}$/cm^3). The high Al-content layers between the LED heterojunction and GaAs buffer layer shown in Fig. 1 is the etch-stop layer for easy substrate removal.

We developed a simple RCLED fabrication process using substrate-removal techniques. In this process, Ag–Au (200 nm/200 nm in thickness) was first evaporated on top of the tunnel diode as the metal contact as well as the high-reflectivity mirror. The wafer was then cleaved and mounted on a Si host wafer (metal side facing down) with epoxy. The GaAs substrates were then lapped and etched away with $H_2O_2 : NH_4OH$ (ratio $= 19 : 1$). The etching rate slows down in the high-Al content etch-stop layers after the complete GaAs substrate removal. The high Al-content layers were then removed by a HF solution, leaving a smooth surface. At this stage, the 1.5-μm thin-film cavity material has been flipped and attached to a host Si substrate with a high-reflectivity Ag mirror/ohmic contact underneath it. The substrate-removal technique used here is very reliable and repeatable. We have achieved a success rate higher than 95% in our experiments. After the substrate removal, we processed the devices in the same way as the nonresonant-cavity LEDs, which includes a mesa etch (mesa diameter $= 100\mu$m), Si_3N_4 dielectric deposition and Ti–Au ring contact patterning. As the final step, we deposited a thin layer of Ag (25 nm) on top of the mesa as the low reflective mirror ($R \approx 70\%$ estimated from theory). For comparison, we also processed nonresonant-cavity LEDs from the same wafer by evaporating a Ti–Au contact to the bottom of the substrate and patterning a Ti–Au ring contact on top of the tunnel diode. The emission window for both types of LEDs is 60 μm in diameter.

III. EXPERIMENTAL RESULTS

To test device performance, we first measured the I–V characteristic of our RCLEDs. Fig. 2 shows the measured current density versus applied external voltage. It shows that the device exhibits a typical p–n junction diode behavior. The addition of tunnel diode did not change the LED's diode behavior, indicating that the tunnel diode acts as a good contact for the RCLED. We also found that the heavily doped tunnel diode layers significantly spreads the lateral current flow, decreasing the current crowding around the contact area, therefore increasing LED emission uniformity.

To evaluate the resonant-cavity effect, we compared the optical emission spectra from the RCLEDs and nonresonant-cavity LEDs. The emission spectra of both devices are plotted in Fig. 3. Compared to nonresonant-cavity LEDs (spectral linewidth full-width at half-maximum (FWHM) ≈ 50 nm), we observed a linewidth reduction of more than twofold in the RCLEDs (spectral linewidth FWHM $\approx$ 20 nm). Note that the measured linewidth of the RCLEDs is still larger than expected. This may indicate that the actual mirror reflectivity of the RCLED is smaller than that predicted in theory. The RCLED emission is centered at 896 nm, which is only less than 1% off the designed value ($\lambda = 890$ nm). This shows that we have precise control over the cavity length during the cavity growth and device processing.

The total emission power of the nonresonant-cavity LED (all light coupled to air) was measured to be 4 μW/mA. The quantum efficiency of this device is consistent with our previous result [7] and is among the highest for the high-speed LEDs. The total emission power of the RCLED is estimated to be ~8 μW/mA. This output emission power can be further improved through decreasing the cavity length of the RCLED. To compare the fiber-coupled power, we butt-coupled our devices with a multimode fiber of 50-μm core diameter. The fiber-LED distance was controlled at 1 mm. Fig. 4 illustrates the fiber-coupled power versus pump current for both the RCLEDs and nonresonant-cavity LEDs. For pump currents less

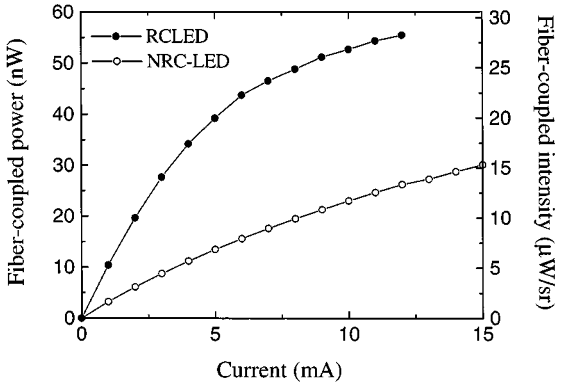

Fig. 4. Fiber-coupled power versus pump currents for the RCLEDs and nonresonant-cavity LEDs.

than 5 mA, the lensless fiber-coupled power from the RCLEDs is ~4 μW/sr/mA. This is more than three times higher than that from the noncavity LEDs (~1.2 μW/sr/mA). We note that the improvement in fiber-coupled power is mainly attributed to the improved emission directionality by the resonant-cavity effect. Further improvements on fiber coupling efficiency and linewidth can be expected through increasing the mirror reflectivity with optimized device fabrication process.

IV. CONCLUSION

We have demonstrated a new design and technique to incorporate a tunnel diode into the high-speed low-cost LED structure. The use of the tunnel diode enables the easy fabrication of a metal-mirror cavity for the RCLEDs. This design is especially important for those material systems where semiconductor DBR material is difficult to grow.

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