Resonant cavity light-emitting diode

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A novel concept of a light-emitting diode (LED) is proposed and demonstrated in which the active region of the device is placed in a resonant optical cavity. As a consequence, the optical emission from the active region is restricted to the modes of the cavity. Resonant cavity light-emitting diodes (RCLED) have higher spectral purity and higher emission intensity as compared to conventional light emitting diodes. Results on a top-emitting RCLED structure with AlAs/$Al_xGa_{1-x}As$ quarter wave mirrors grown by molecular beam epitaxy are presented. The experimental emission linewidth is 17 meV (0.65 kT) at room temperature. The top-emission intensity is a factor of 1.7 higher as compared to conventional LEDs.

In this letter, a new concept of a resonant cavity light-emitting diode (RCLED) is proposed in which the active region is placed into a resonant optical cavity. The cavity is defined by a highly reflective ($R_1 \cong 0.99$) and a moderately reflective ($R_2 \cong 0.90$) mirror. The optical properties of the RCLED are superior, while the fabrication process complexity is comparable to conventional LEDs. This letter is dedicated to the proposal, analysis, and the demonstration of the new resonant cavity light-emitting diode. The structure of the RCLED in the $Al_xGa_{1-x}As$/GaAs material system is shown in Fig. 1. The RCLED consists of a distributed Bragg reflector, i.e., 20–30 *n*-type AlAs/$Al_xGa_{1-x}As$ quarter wave pairs, and *n*-type confinement region, an active region, a *p*-type confinement region, and a top semitransparent/semireflective mirror. The optical cavity mode is in resonance with the spontaneous emission of the active region. The placement of the active region results in several clear advantages of the RCLED over conventional LEDs[1] which are outlined in the following.

First, enhanced spontaneous emission can be obtained in RCLEDs which result from the placement of the active region into a resonant optical cavity. It is well-known that the probability for spontaneous emission is proportional to the matrix element of the initial and final electron state and proportional to the optical mode density. The optical mode density in a Fabry–Perot resonator is strongly enhanced for on-resonance wavelengths. As a consequence, on-resonance transitions of the RCLEDs are enhanced. Previously, it has been demonstrated experimentally that the spontaneous lifetime of a medium changes drastically, upon placement of the medium in a optical cavity.[2–4] Changes in spontaneous emission lifetime exceeding a factor of 10 for high-finesse optical cavities have been reported.[2] The carrier lifetime change is due to the varying optical mode density in a Fabry–Perot cavity. While off-resonance optical transitions have a longer lifetime, on-resonance transitions have a shorter lifetime.[2] Spontaneous emission of the RCLED is, therefore, "channeled" into the optical resonance modes of the cavity. Note that a decrease in spontaneous lifetime makes nonradiative Shockley–Read processes less important. Rogers *et al.*[5] showed that the spatial placement of the active region into the optical antinode position results in further enhancement of the emission intensity. Raja *et al.*[6] proposed and realized a structure in which a periodic active medium was placed at the optical antinode positions in a vertical cavity laser which increased the gain by a factor of two.

Second, emission of light through the contact side ("top side") is enhanced due to the highly reflective mirror adjacent to the *n*-type confinement layer ("bottom side"). Light emission in conventional LEDs is typically close to isotropic.[1] In the RCLED structure, however, the bottom reflector has a higher reflectivity than the top reflector, i.e., $R_1 \gg R_2$. As a consequence, light propagating along the optical axis of the cavity exits the cavity predominantly through the top (low reflectivity) mirror. The anisotropic emission spectrum of the RCLED can enhance the emission through the top side by a factor of two.

Third, the improved spectral purity of the RCLED makes the device well suited for optical communication purposes. Conventional LEDs have spectra linewidths determined by the density of states in the conduction and valence band and the thermal energy of carriers. Typical linewidths are on the order of 1.8 kT, where kT is the thermal energy. A better spectral purity can be achieved with the RCLED. Since the spontaneous emission from the active region is constrained to emit into the modes of the optical cavity, the finesse of the cavity allows one to estimate the linewidth of the RCLED. The cavity Q of a co-

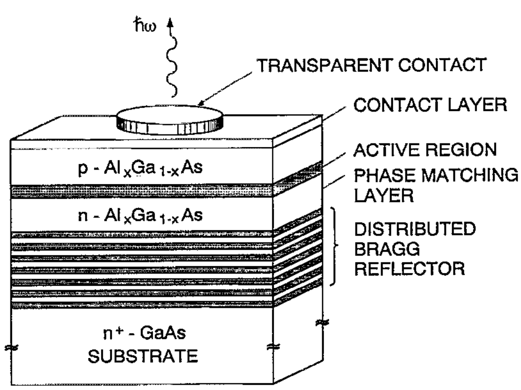

FIG. 1. Schematic layer sequence of the resonant cavity light-emitting diode (RCLED).

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planar Fabry–Pérot cavity is given by[5]

$$Q = \frac{\nu}{\Delta\nu} = 2\pi \frac{L_c}{\lambda} (- \ln \sqrt{R_1 R_2})^{-1}, \quad (1)$$

where L_c is the cavity length, and $\Delta\nu$ and ν are the bandwidth and frequency of the Fabry–Pérot resonance mode, respectively. As an example, we choose $L_c = \lambda$, $h\nu = 1.42$ eV, and $R_1 R_2 = 0.9$, which yields $Q \cong 120$. The corresponding linewidth is $h\Delta\nu \cong 12$ meV which is much narrower than kT at room temperature. Due to the inherently high spectral purity of the RCLED, the device is expected to have less chromatic dispersion in silica fibres.

Note that the resonant cavity light-emitting diode is structurally related to vertical cavity surface-emitting lasers with semitransparent/semireflective top contacts.[7] However, the two device structures serve different purposes and have different design characteristics. For example, mirror reflectivities exceeding 99% are essential for low threshold operation of the lasers. For the RCLED, a top mirror reflectivity of 90% is sufficient, i.e., the requirements for the two mirrors are less stringent for the RCLED.

The resonant cavity light-emitting diode structures were grown by molecular beam epitaxy on (001) oriented n^+-type GaAs substrates. The layer sequence consists of an n-type $AlAs/Al_{0.14}Ga_{0.86}As$ distributed Bragg reflector, the lower n-type $Al_{0.30}Ga_{0.70}As$ bottom confinement layer ($t = \lambda/2 \cong 1400$ Å), a thin GaAs active region ($t = 100$ Å), a p-type $Al_{0.30}Ga_{0.70}As$ top confinement layer ($t = \lambda/4 \cong 700$ Å) and a thin heavily Be-doped p^+-type $Al_{0.14}Ga_{0.86}As$ layer to facilitate ohmic contacting. Thin Ag films (200–500 Å) and very thin Ag films (50 Å) covered by the transparent conductor cadmium tin oxide ($CdSnO_x$) were used as top electrodes which served as contacts as well as top reflectors. Additional current guiding (e.g., mesa-etch or proton implantation) is not required in the structure due to the small amount of current spreading occurring. The Ag and $Ag/CdSnO_x$ contacts have excellent ohmic characteristics. The thin Ag and $Ag/CdSnO_x$ films have reflectivities ranging from approximately 50% and 97% as determined by an Anritsu MS9001B optical spectrum analyzer and an incandescent "white" tungsten light source. The thin Ag contacts were found to have lower resistance but higher optical absorption than the $Ag/CdSnO_x$ contacts.

The current-voltage (I-V) characteristic of the resonant cavity light-emitting diode structure is shown in Fig. 2 for a 20 μm diameter contact. The I-V characteristic exhibits a "turn-on" voltage of 1.4 V and a high differential conductivity (dI/dV) indicating a low series resistance of the structure. The diode voltage does not exceed 2.0 V. Such low voltages are difficult to achieve in structures with epitaxially grown p-type $AlAs/Al_xGa_{1-x}As$ top mirrors.[7] Note that the growth and processing requirements (e.g., mirror reflectivity) of the RCLED are significantly less stringent as compared to vertical cavity lasers.[7]

The optical power versus injection current characteristic of the RCLED measured at room temperature is shown in Fig. 3. The light output power was measured

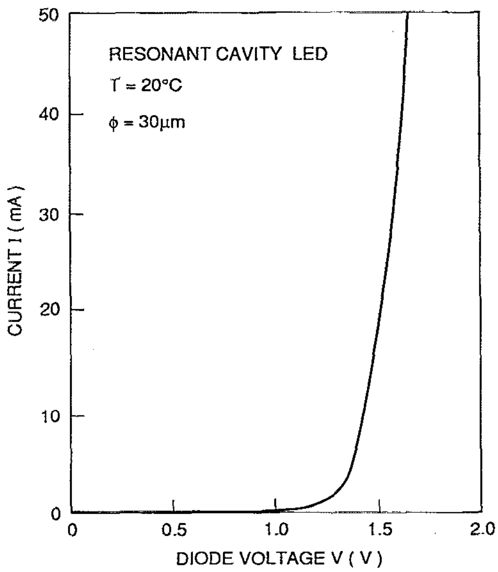

FIG. 2. Current-voltage characteristic of a resonant cavity light-emitting diode.

with an ANDO AQ1125 optical power meter. The optical output power depends linearly on the injection current. The linear dependence is expected for the spontaneous emission regime and indicates the absence of super-luminescence and stimulated emission. Nonlinear emission spectra can also arise from saturable absorbers in the cavity. The absence of light versus current nonlinearities, i.e., reabsorption processes, indicates the high quality of the epitaxial growth.

The linewidths of the RCLED emission spectra are narrower than the emission spectra of conventional LEDs. As stated above, the usual spontaneous linewidth is approximately 1.8 kT which corresponds to $\Delta\lambda \cong 28$ nm for $\lambda = 870$ nm at room temperature. The spontaneous electroluminescence emission spectrum of the RCLED is shown in Fig. 4. The emission peaks at $\lambda = 862$ nm and has a full width at half-maximum of 17 meV ($\Delta\lambda = 10.5$ nm). The experimentally measured linewidth is much nar-

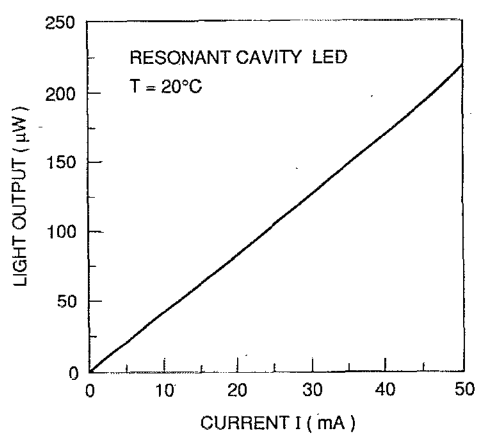

FIG. 3. Optical output power vs injection current of a resonant cavity light-emitting diode at room temperature.

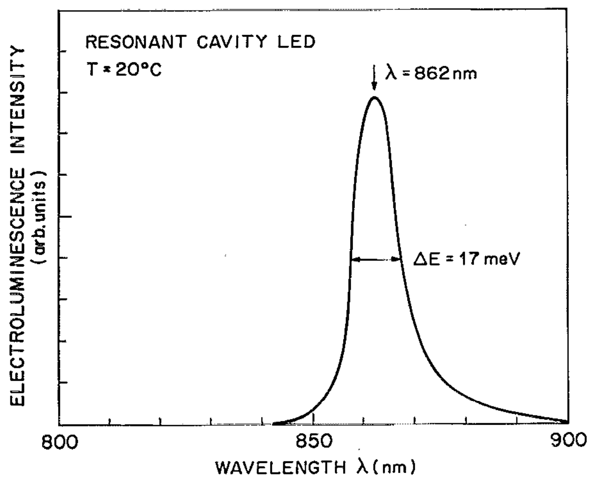

FIG. 4. Electroluminescence spectrum of a resonant cavity light-emitting diode at room temperature. Note that the spontaneous luminescence linewidth is narrower than kT at room temperature.

rower than expected for spontaneously emitting conventional LEDs, which have typical linewidths of 1.8 $kT = 45$ meV at room temperature. Note that even broader linewidths (e.g., 50–90 meV) were measured in conventional GaInPAs LEDs emitting at 1.3 μm.[1] Our results are in qualitative agreement with Rogers *et al.*,[5] who found a reduction of the spontaneous photoluminescence linewidth by a factor of four upon confining a quantum well by an optical cavity. As stated above, the emission linewidth is a function of the finesse of the cavity. Thus, the linewidth is not a fixed parameter but can be *designed* by means of the cavity characteristics. For applications of the RCLED in silica fibre applications, the spectral purity is of importance and can be achieved by a high finesse cavity design.

Finally, the RCLED intensity emitted through the top surface is compared to a conventional LED structure without an optical cavity. The emitted power is measured with a broad-area Si-detector (Ando AQ1125 optical power meter). The intensity of the RCLED is found to be a factor of 1.7 higher as compared to a conventional LED structure. The increase in intensity is attributed to the unequal reflectivities of the two mirrors ($R_2 > R_1$) and to a decreased spontaneous lifetime of the RCLED structure. Further experiments are required to estimate the relative contribution of the two effects.

In conclusion, a novel device concept, the resonant cavity light-emitting diode (RCLED) is proposed and demonstrated. The active region of the diode is located inside a high finesse optical cavity. Spontaneous emission from the active region is restricted to the optical modes of the cavity. As a result, the spectral purity of the RCLED is improved over conventional LEDs, i.e., the spectral linewidth is narrower than kT. The light-output intensity of the RCLED is enhanced by using cavity mirrors with unequal reflectivities and by placing the active area into an antinode position of the optical intensity within the cavity. The device concept is demonstrated in the AlAs/GaAs material system grown by molecular beam epitaxy. Quarter wave AlAs/$Al_{0.14}Ga_{0.86}As$ mirrors with high reflectivity ($R_1 \cong 99\%$) are used for the substrate-sided (bottom) mirror. Lower reflectivity Ag and Ag/$CdSnO_x$ mirrors are used for the top mirror. The devices have a linear light-output versus current characteristic and excellent electrical characteristics.

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[1] R. H. Saul, T. P. Lee, and C. A. Burrus, in *Semiconductors and Semimetals*, edited by R. K. Willardson, A. C. Beer, and W. T. Tsang (Academic, New York, 1985), Vol. 22, Part C, p. 193.
[2] F. De Martini, G. Innocenty, G. R. Jacobovitz, and P. Mataloni, Phys. Rev. Lett. **59**, 2955 (1987), see also E. M. Purcell, Phys. Rev. **69**, 681 (1946).
[3] H. Yokoyama, K. Nishi, T. Anan, H. Yamada, S. D. Brorson, and E. P. Ippen, Appl. Phys. Lett. **57**, 2814 (1990).
[4] M. Suzuki, H. Yokoyama, S. D. Brorson, and E. P. Ippen, Appl. Phys. Lett. **58**, 998 (1991).
[5] T. J. Rogers, D. G. Deppe, and B. G. Streetman, Appl. Phys. Lett. **57**, 1858 (1990).
[6] M. Y. A. Raja, S. R. J. Brueck, M. Osinski, C. F. Schaus, J. G. McInerney, T. M. Brennan, and B. E. Hammons, Electron. Lett. **24**, 1140 (1988).
[7] L. W. Tu, E. F. Schubert, R. F. Kopf, G. J. Zydzik, M. Hong, S. N. G. Chu, and J. P. Mannerts,. Appl. Phys. Lett. **57**, 2045 (1990); L. W. Tu, E. F. Schubert, H. M. O'Bryan, Y.-H. Wang, B. E. Weir, G. J. Zydzik, and A. Y. Cho, *ibid.* **58**, 790 (1991).