Tunnel-junction-connected distributed-feedback vertical-cavity surface-emitting laser

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An injection distributed-feedback vertical-cavity surface-emitting laser (VCSEL) with tunnel junctions served as quasi-Ohmic intercontacts (tunnel-junction-connected distributed-feedback VCSEL) is proposed. A periodic structure of vertically stacked double-heterostructure laser diodes connected by low-resistance tunnel junctions forms a vertical distributed-feedback (DFB) laser medium. To minimize the threshold, the DFB structure is placed in a Fabry–Perot cavity designed to match gain layers with the maximums of the optical mode, and the tunnel junctions—with its minimums. The passive regions with tunnel junctions provide effective vertical injection into each active region of this multiple-active-region laser. This DFB VCSEL is expected to have an improved performance, specifically, reduced threshold current and heightened output power. © *1998 American Institute of Physics.* [S0003-6951(98)02937-4]

Over the past few years, the performance of vertical-cavity surface-emitting lasers (VCSELs) has been improved considerably due to introduction of selective oxidation[1–3] and low-resistance distributed Bragg reflectors (DBRs).[4] While the low-power (~1 mW) characteristics of modern VCSELs are now comparable to or even better than those of edge-emitting lasers, high-power (~1 W) VCSELs are still not available. The main obstacle for increasing their output power is a small gain region that requires very high-reflecting mirrors to obtain generation. Therefore, a VCSEL operates at a higher internal temperature than an edge-emitting laser, and thermal rollover limits the output power of the VCSEL to smaller values. Progress in developing a long-wavelength VCSEL also meets difficulties. They are in constructing high-reflecting mirrors and high-gain active regions, which are unavoidable in the existing VCSEL design.

In this letter, we propose and substantiate a design for the injection VCSEL with multiple active regions (ARs), which combines a number of vertically stacked conventional double-heterostructure pumping *pin* diodes connected in series within a single vertical waveguide. These *pin* diodes consist of *p*- and *n*-type wide-band-gap regions that inject carriers into a double-heterostructure narrow-band-gap *i*-type AR with one or several quantum well (QW) gain layers. Tunnel junctions (TJs) serving as quasi-Ohmic contacts provide the effective current connection of the *pin* diodes in series. The *p* and *n* regions of two adjacent *pin* diodes with the p^+n^+ TJ between them form a passive region (PR). Alternation of quarter-wave high-index ARs with QW gain layers and quarter-wave low-index PRs with the TJ in the middle forms a distributed-feedback (DFB) laser medium, shown in Fig. 1. The coupling constant for this DFB VCSEL is much greater than for a conventional edge-emitting DFB laser with periodic grating because of a larger difference in refracting indexes accessible with this multilayered structure. As a result, the effect of the feedback becomes noticeable in shorter structures with a smaller number of periods. The dominant parasitic losses in the structure are in the high-loss TJs and *p*-type regions. To decrease these losses and to link the quasistanding wave with a periodic gain/loss structure, the DFB structure is placed between two mirrors that form a Fabry–Perot (FP) laser cavity. As a result, the TJs are matched with the minimums of the cavity mode. Also, to minimize optical losses in the *p*-type regions, these regions must be almost completely depleted at operation voltages, but not too much to provide sufficient injection. Heavily

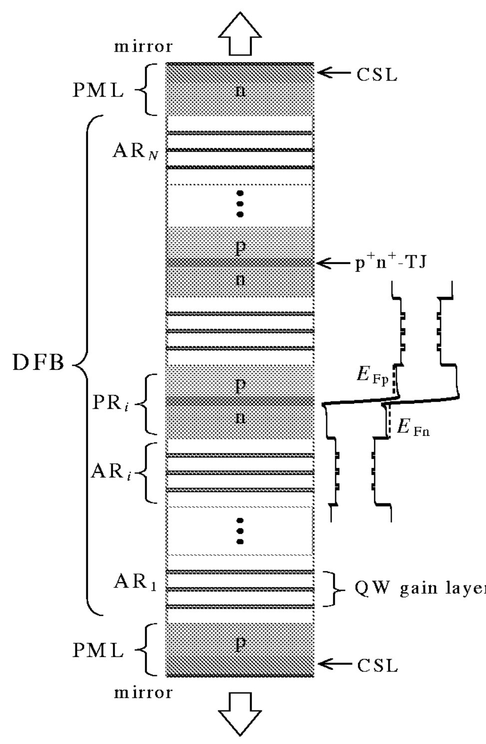

FIG. 1. Model design for the tunnel-junction-connected DFB VCSEL. DFB structure contains N ARs and $N-1$ PRs. PML and CSL are phase-matching and current-spreading layers. Schematic energy-band diagram presents two double-heterostructure pumping diodes connected by a narrow TJ. E_{Fn} and E_{Fp} are electron and hole Fermi levels in the n and p-type regions.

[a)]Electronic mail: korshak@ciao.eng.wayne.edu doped current-spreading layers (CSLs) near the mirrors form low-resistance contacts to the device (see, for example, Ref. 5).

The considered model of a GaAs/AlAs DFB VCSEL is shown in Fig. 1. The DFB structure contains N GaAs ARs of 69.6 nm width and N-1 AlAs PRs of 83.1 nm width that corresponds to the Bragg wavelength λ_0 of 0.98 μm. It is placed in a FP laser cavity formed by the mirrors of reflectivity r. Optical gain g is obtained in the QW gain layer of 42 nm width, and optical absorption α is in the TJs of width w. Characteristic values for α and w are taken to be 1000 cm^{-1} and 20 nm (with a net loss per TJ, αw, of 0.002), respectively. Typical free-carrier absorption in p- and n-type doped PRs is less than 20 cm^{-1}, which gives a net loss per PR no more than 1.2×10^{-4}. Therefore, optical losses in these layers can be neglected. The optimal design of the cavity with a minimum threshold includes AlAs phase-matching layers (PMLs) placed between the DFB structure and the mirrors. These layers formed by the heavily doped current-spreading layers and p- and n-type regions serve as emitters for the first and the last ARs. The minimum threshold is achieved at a wavelength λ, which does not coincide with λ_0. Both the matching phase ϕ and the wavelength λ depend on the number of the layers in the DFB structure and on the reflectivity of the mirrors forming the FP cavity. For a 10 AR laser with the mirror reflectivity of 0.98, we have $\phi\approx\pi/2$ and $\lambda\approx1.08$ μm.

Contemporary VCSEL designs use a FP resonant cavity with quarter-wave semiconductor DBRs to reach very high mirror reflectivity. Usually, each DBR consists of 20 or more periods of index gratings. Thus, the total length of the VCSEL usually exceeds 20 wavelengths, while the gain length is just a few tenths of the wavelength. Since the propagation losses in the huge DBRs are dominant over parasitic losses in a modern VCSEL, they effectively limit the further improvement of laser characteristics. The multiple AR design diminishes the mirror losses per AR in proportion to the number N of diodes in series, so that the required gain per AR is mainly limited by the propagation losses in a *pin* diode. If it is designed to match gain layers with the maximums of the optical mode and the TJs with its minimums, the optical losses could be smaller than in a conventional VCSEL. Figure 2 demonstrates a reduction in the threshold gain for the proposed DFB VCSEL. It can be seen that the threshold gain for an optimally designed DFB structure containing 10 ARs with the mirror reflectivity of only 98% is as low as 390 cm^{-1}.

Figure 2 also shows that the required reflectivity of mirrors decreases as the number of the ARs increases, which is a result of increasing feedback. Even for a structure with a relatively small number of the periods ($\geqslant$7), metal coatings with reflectivity of about 0.97 can be used as the mirrors.

Naturally, the threshold voltage for a stack of *pin* diodes connected in series increases in proportion to the number of the diodes, so that the threshold power becomes N times greater than that for a conventional VCSEL, if the threshold current remains the same. This, in turn, leads to an increased output power of the DFB VCSEL. If the TJ is designed properly to minimize voltage drop over the PRs keeping low free carrier and electroabsorption, the conversion efficiency for

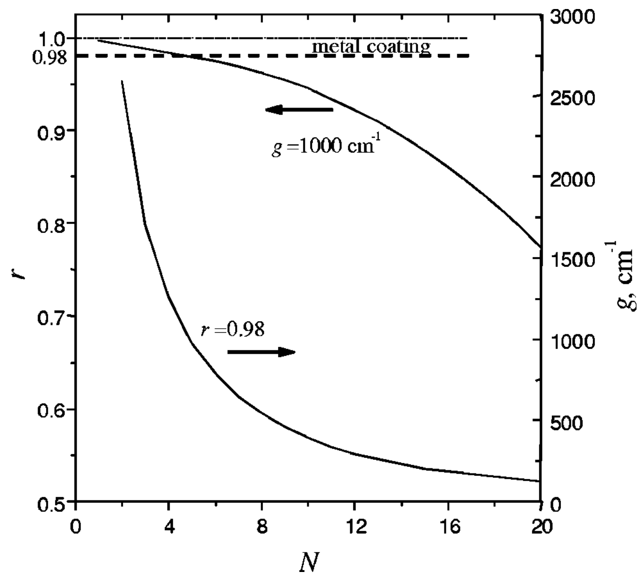

FIG. 2. Reflectivity of the mirrors r that is required to achieve lasing, and threshold gain g as a function of the number of ARs in the DFB VCSEL. When calculating $r(N)$, the gain g is assumed to be 1000 cm^{-1}. For the curve $g(N)$, mirror reflectivity is taken to be 98%.

the proposed VCSEL will be comparable to that for a conventional VCSEL.

An increment of the current above the threshold in the structure of the diodes connected in series results in an increase in the number of photons generated in each diode, so that the number of photons per electron in the current increment increases in proportion to the number of diodes. Therefore, the slope of the light–current characteristic, that is, the differential quantum efficiency, is N times higher than for a conventional VCSEL. Consequently, a higher output power is achieved at lower currents where the conversion efficiency has a maximum.

Preceding studies of the absorption of laser light in semiconductors have focused mainly on free-carrier absorption, while electroabsorption in high electric field ($>10^6$ V/cm) remains quite poorly studied. Despite the rapid growth of the absorption coefficient in high electric fields, optical losses in a TJ cannot be expected to be very high because of its small size. This conclusion is confirmed by numerical calculations of the threshold gain dependence on the absorption loss in the TJs and on their width in the 10 AR DFB VCSEL with mirror reflectivity 94.5% shown in Fig. 3. An increase in the TJ loss from 500 up to 3000 cm^{-1} results in a much slower increase in the threshold gain from 966 to 1130 cm^{-1}. Similarly, widening of the high-loss region from 130 to 400 Å raises the threshold gain from 975 to 1089 cm^{-1} only. Numerical modeling shows that an optimized design of the proposed tunnel-junction-connected DFB VCSEL has low sensitivity to the details of the TJ connecting layers because these layers are located in the quasinulls of the laser mode.

TJs are widely applied in modern optoelectronics: in tandem and multielement solar cells[6] to increase a conversion efficiency, in edge-emitting[7,8] and surface-emitting[9] laser designs to substitute poorly conducting p-type contacting layers by highly conducting n layers. Also, heavily doped p^{++} layers[5] with carrier concentration of 1×10^{20} cm^{-3} are used to allow a nonalloyed low-resistance p-Ohmic contact to the

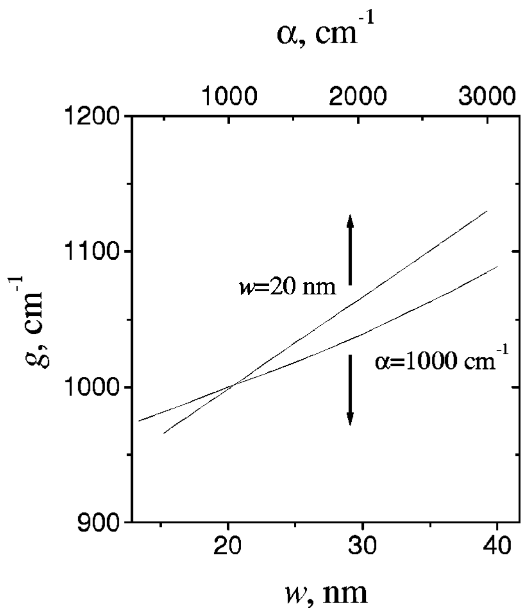

FIG. 3. Dependence of threshold gain g on optical absorption α and on the width w of the TJ for the ten-period DFB VCSEL with $r=0.945$, $g=1000\ \mathrm{cm}^{-1}$, $w=20$ nm for $g(\alpha)$ curve, and $\alpha=1000\ \mathrm{cm}^{-1}$ for $g(w)$ curve.

device. All these designs show that optical losses due to free-carrier absorption and electroabsorption in the structures with TJs are sufficiently low to be acceptable for the proposed laser design.

In conclusion, we have described the design and characteristics of the tunnel-junction-connected DFB VCSEL. This electrically pumped VCSEL with multiple ARs eliminates the need for extra high-reflecting mirrors in a conventional VCSEL. We predict that metal coating can be used as the mirrors for the DFB VCSEL with more than seven periods and threshold gain can be less than 400 cm^{-1} for a 10 AR structure. Optical absorption in the TJs and their width do not affect the threshold considerably because in the properly designed structure the TJs are located in the minimums of the optical standing wave.

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