Enhanced electro-optic modulation by integration of non-radiative centers in a resonant tunneling light emitting diode

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We create a reservoir of hole traps in a resonant tunneling light emitting diode by etching the p-type contact into an array of nanometer scale pillars. In the off state, the charge reservoir keeps the light output extremely low, even at relatively high currents. The device can be switched on to produce light by raising the electron emitter past a confined electron state allowing holes to escape from the nonradiative region. The resulting electro-optic switch has an on/off ratio of at least 1000:1, a large improvement over conventional resonant tunneling light emitting diodes. © *1997 American Institute of Physics.* [S0003-6951(97)00625-6]

Recently, it has been shown that resonant tunneling light emitting diodes (RTLEDs) can function as electro-optical switching devices.[1] An RTLED consists of a p-i-n GaAs light emitting diode in which the i-GaAs region is replaced by a double barrier quantum well (QW).[2] The current through a RTLED decreases sharply with increasing applied bias as the bottom of the conduction band in the emitter moves past a confined state in the QW. In contrast to n-i-n resonant tunneling diodes, switches associated with hole as well as electron states are observed.

The primary interest in RTLEDs for device applications results from the bias dependence of the electroluminescence. As the current switches through a resonance, the luminescence intensity also switches, due to the sudden decrease in current and the redistribution of electron and hole populations among the n, p, and QW regions. The light output can increase or decrease through the resonance, depending on how the charge redistributes.[3] In this way, a bistable electro-optic switch can be made. The on/off ratio of the electroluminescence is small however; electron and hole currents switch at different biases, so that the light output is never completely shut off (or turned on) by any one switch. This is a serious drawback when considering optical switching applications.

In this letter, we present measurements for a new type of RTLED structure in which the *decrease* of current following a resonant switch directly *enhances* the radiative recombination process. In our device, holes are trapped in a nonradiative array of pillars on the p side of the device. The hole escape rate is inhibited by the flow of electrons through the double barrier so that when the electron current drops after the resonance, the holes simultaneously escape and are able to recombine radiatively. The electroluminescence then turns on exponentially from a completely off state. In this way, we are able to create an electro-optic switching device with an on/off ratio of 1000:1.[4]

Our device is shown schematically in Fig. 1. It is fabricated from a p-i-n GaAs/AlGaAs double barrier heterostructure, MBE grown on an n^+ GaAs substrate. The quantum well is undoped, with 11 nm thick $Al_{0.33}Ga_{0.67}As$ barriers and a 9 nm thick GaAs well. The GaAs layers on either side of the double barrier are 250 nm thick; the doping is graded between the heavily doped contact region to the undoped quantum well: 100 nm, 2×10^{18}/80 nm, 2×10^{17}/40 nm, 2×10^{16}/30 nm, undoped. We define our device area by wet etching, and then isolate the top contact mesa using a 300 nm Si_3N_4 film sputtered onto the exposed n^+ substrate. The p^+ surface layer is etched into an array of nanoscale pillars using the granular lithographic technique that has been described previously.[5] SEM analysis reveals that the pillar etch depth is approximately 150 nm and that the pillars are between 20 and 50 nm in diameter. We make contact to the pillars using a sputtered Indium/Tin Oxide (ITO) transparent film.[6]

The solid line in Fig. 2 [(a) linear scale, (b) log scale] shows the current through an (80 μm)^2 pillar array RTLED as a function of bias at 4.2 K. The current increases exponentially after the bias reaches 1.2 V; below this point only a small leakage current ($<$10 pA), is measurable. The device also remains off in the negative bias direction—no hysteretic switching, similar to that measured in n-i-n pillar devices,[5] is observed. At 1.82 V the current reaches a peak of 517 nA, and then drops by more than a factor of 4, to a minimum of 122 nA at 1.91 V. A second, much smaller feature is observed near 2 V. Further measurements demonstrate that the IV characteristics are reproducible even after thermal cycling, and that the current scales with the device area.

According to calculations,[7] the quantum well in our device contains two confined electron states (36 and 132 meV

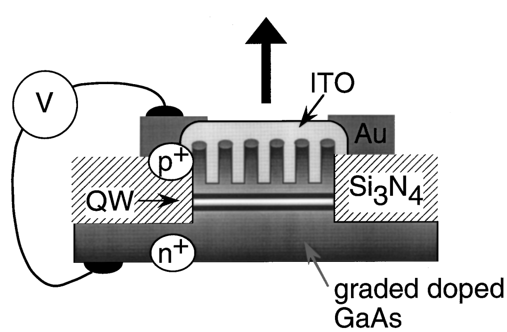

FIG. 1. Schematic drawing of the RTLED pillar array device. Pillars were etched for 1.6 minutes in 10 mTorr $SiCl_4$:Ar at a ratio of 1:2 with a power density of 4 mW/cm^2. The quantum well remains unetched and optically active.

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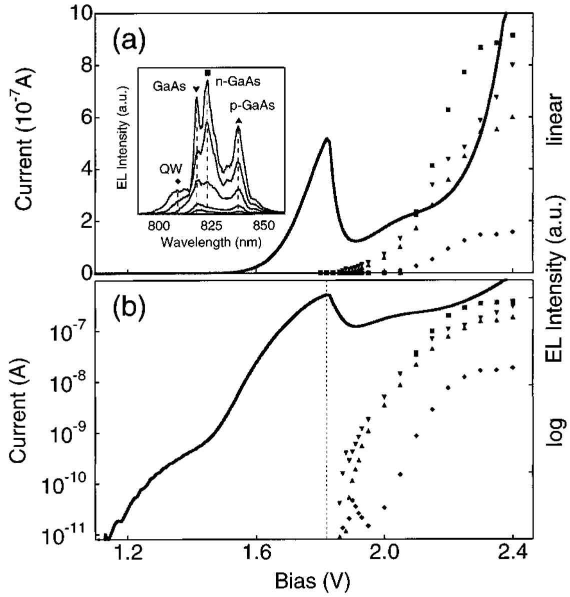

FIG. 2. Current versus bias (solid line) compared with electroluminescence intensity (symbols) measured at 4.2 K and plotted on (a) linear and (b) log scales. The dotted line in (b) is drawn at the resonance bias. The symbols correspond to the height of the four luminescence peaks shown in the inset; here the electroluminescence is plotted as a function of wavelength for biases of 1.92, 2.00, 2.10, 2.20, and 2.40 V.

above the GaAs conduction band) and a spectrum of seven confined hole states (four heavy hole and three light hole). Characteristics of non-pillar RTLEDs (measured by ourselves and others[2,3,8]) suggest that the main peak in Fig. 2 is associated with the higher electron state. Peaks associated with the hole states, which are visible in the nonpillar device characteristics, are absent from the pillar device IV. This implies that very little hole current is present in the pillar devices before the electron resonance.

We measure the electroluminescence of the pillar devices by focusing the collected light from a 5 μm diameter spot onto the input slit of a spectrometer/cooled CCD detector. The inset of Fig. 2(a) shows the emitted light intensity as a function of wavelength as the forward bias increases across the device. The first measurable light appears at 1.86 V—after this point the light intensity increases rapidly with increasing bias. At 2.4 V (which corresponds to the highest intensity trace in the figure) four main peaks are observed. We attribute these to the four main recombination processes that occur in a RTLED:[4] (1) electrons from the conduction band recombine directly with holes in the valence band (GaAs peak); (2) electrons bound to the donor atoms recombine with valence band holes (p-GaAs peak); (3) holes bound to the acceptor atoms recombine with conduction band electrons (n-GaAs peak); (4) electrons and holes recombine in the quantum well (QW peak). Notice that at low biases, only the GaAs and p-GaAs peaks are present—initially, recombination takes place only on the p side of the device.

In the main part of Fig. 2 the heights of the four peaks—GaAs (upside-down triangles), p-GaAs (triangles), n-GaAs (squares), and QW (diamonds)—are plotted as a function of bias. Comparison with the IV characteristic shows that the light emission turns on just at the electron resonance, even though the current starts to decrease at this point. The light intensity shoots up exponentially with increasing bias, and rises by three orders of magnitude by the time the current returns to the peak value of 517 nA. This unusual behavior is not observed in comparative measurements of nonpillar RTLEDs (not shown); in these, the light intensity turns on at low bias prior to the main resonance and decreases through regions of negative differential resistance. If the detector position is kept constant, the EL spectrum of the pillar devices is reproducible and no hysteresis is observed in the bias dependence.

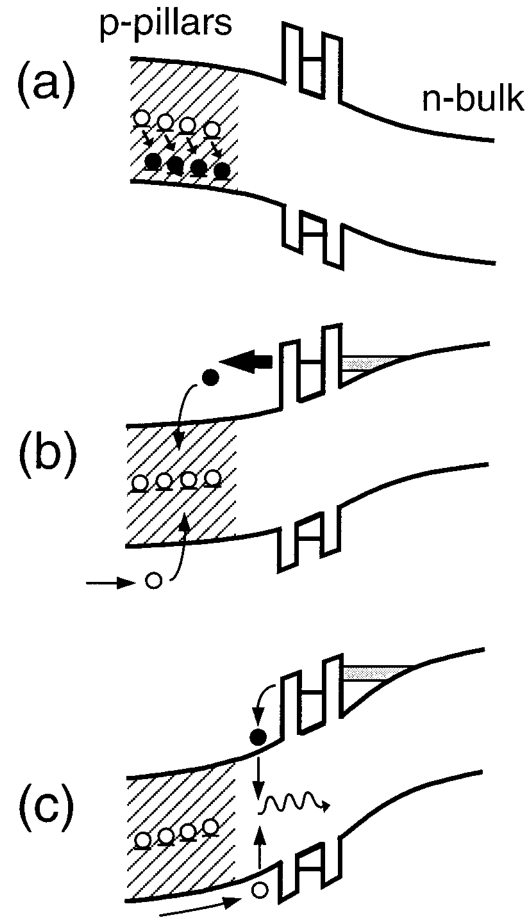

FIG. 3. A schematic band diagram of the pillar array RTLED for (a) zero bias (b) before resonance, and (c) after resonance (see text). The shading indicates the pillar etch depth. The region to the left of the p pillars (not shown) is more heavily doped, and is not completely depleted of holes.

We can understand the anomalous EL in the pillar devices by considering the influence of non-radiative surface states on electron-hole recombination. Figure 3(a) shows the band diagram of the pillar array RTLED at zero applied bias. Depicted is the more lightly doped region on either side of the double barrier. The precise surface state distribution is unknown, however, it is likely that etching the pillar array creates a series of donor trap states near midgap, and above the dopant acceptor level.[9] The acceptor states are thus filled by electrons from the donor trap states. This depletes the valence band of holes that would normally be present in the bulk material.

If a forward bias larger than the built-in potential is placed across the junction [Fig. 3(b)], electrons from the n-bulk region will be injected through the double barrier and into the pillars. These electrons will quickly drop into the surface states made available by the acceptor dopant atoms. Any holes that are injected from the p^+ contact region will recombine with the electrons indirectly via the surface states before reaching the double barrier and the n-bulk side of the junction. Nonradiative recombination dominates because of the large reservoir of surface states and the small matrix element for radiative emission from trapped charges.[10]

As the bias increases, the rate of holes injected from the p^+ region increases, but continues to be compensated by the flow of electrons. Eventually, the bottom of the conduction band in the n-bulk region moves past the confined electron level in the well. This results in a decrease in the flow of electrons, and thus creates the negative differential resistance shown in Fig. 2. After the resonance, there are not enough electrons to recombine with the holes in the trap region, which are then able to flow from the pillars into the p bulk. Here, they recombine radiatively with electrons, which tunnel sequentially, or are thermally excited through the QW into the p-region [Fig. 3(c)]. At higher biases, the holes move into the n region, producing the full spectrum seen in the inset to Fig. 2.

The trapping of holes in the nonradiative pillar array results in an extremely high on/off ratio for the total light output. Before the resonance, the light output is below the noise level of our measurement configuration. After the resonance, when the current increases back to its resonant value, the light output is on the order of 100 μW cm^{-2}—more than three orders of magnitude greater than the noise level. This on/off ratio is much higher than observed in a normal RTLED. The switch can also be driven optically. Experiments demonstrate that illuminating the device with $\approx$500 μW cm^{-2} of 760 nm CW light from a Ti sapphire laser moves the resonance position by -100 mV, enough to cause a switch to the on state.

At low currents (below $\approx$1 mA), the bias dependence of the EL is reproducible, but a large current through the device changes the nature of the EL. After stressing the device at 1 mA for 3 min, the EL bias dependence behaves as it would for a normal RTLED—the light emission increases with increasing current before the resonance, and decreases as the bias moves through the resonance. Figure 4 shows a comparison of the EL measured at 1.9 V before and after the stress current [these measurements were made on a second device with a contact area of $(40\mu\text{m})^2$]. The peak intensity increases by almost two orders of magnitude after stressing. By warming the sample up to 300 K, we are able to return the device to the equilibrium state. As shown in the figure, the EL measured after thermal cycling is almost identical to that measured before the stress.

The reason for this behavior is not completely understood. It is possible that the stress current forces holes into traps, saturating them, so that subsequent holes flow through the pillars, and recombine radiatively in the i region. This temperature dependence provides evidence for a thermally activated trapping mechanism. However, it is difficult to quantify the influence of temperature on the trapping rate due to the strong temperature dependence of carrier transmission over the relatively low AlGaAs barriers. Note that the light emission of the two-terminal device is effectively gated by a charge reservoir integrated into the p-injector. If the charging mechanism were controllable, this would lead to a nonvolatile electro-optical switch. To realize this possibility, more work needs to be done examining the charge dynamics between surface and bulk states.

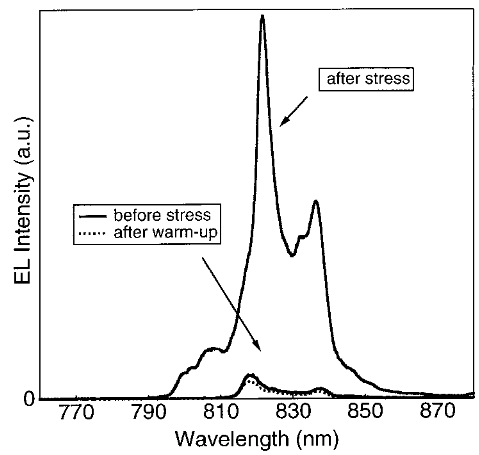

FIG. 4. Comparison of the electroluminescence before and after current stressing, and after thermal cycling to 300 K. The spectrum in each case is taken at a bias of 1.9 V.

In conclusion, we have characterized a novel RTLED device that displays an extremely high on/off ratio in the total light output. Our device integrates a nonradiative pillar array region that traps holes, with an escape rate that depends inversely on the flow of electrons. Light output requires that the electron flow rate decreases through a QW resonance, to allow holes to escape. In the future, we hope to improve the device design for possible electro-optical switching applications.

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