Intensity and spatial modulation of spontaneous emission in GaAs by field aperture selecting transport

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A potential technique for modulating the light emission resulting from excess minority carrier recombination in a semiconductor device is introduced. This process utilizes an electric field to transport a packet of minority carriers past an optical output aperture defined on the surface of the semiconductor. A short burst of light is allowed to escape through the surface of the device as the packet drifts past the opening in the aperture. To first order, the temporal length of the optical pulse will be a function of the width of the excess minority carrier packet, the width of the aperture, and the drift velocity of the excess minority carriers. In p-type gallium arsenide, geometric scales of 5 μm should make possible pulse widths near 100 ps. Initial experimental results are presented confirming the spatial displacement and the attenuation of the external luminescence intensity as a function of applied bias voltage.
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GaAs light-emitting diodes (LEDs) have been studied extensively for their utility in high-speed optical data links.[1–5] Typically, the upper limit for efficient optical modulation in LEDs is determined by the minority carrier radiative recombination lifetime of the semiconductor.[1] Several investigators have attempted to increase the speed of LEDs using a variety of techniques.[2–5] However, the spontaneous radiative recombination lifetime in GaAs is predicted to approach a minimum value of 200–300 ps.[6,7] This phenomenon would make efficient optical modulation beyond 1 Gb/s difficult to achieve. In an attempt to circumvent the high-speed performance restrictions caused by this physical limitation, the utilization of minority carrier drift in a lateral electric field to control the position of the light-emitting region is proposed. As Haynes–Shockley originally reported in 1951, under the influence of an electric field, a minority carrier packet will drift through a semiconductor bar.[8] Therefore, the spontaneous light emission associated with radiative recombination will appear to travel along the bar as well. This letter considers exploiting this capability to develop high-speed light-emitting devices. The potential technique is referred to as field aperture selecting transport (FAST).

A cross-sectional view of the FAST concept is illustrated in Fig. 1. Consider the output aperture defined by two opaque metal electrode contacts deposited on a direct band gap p-type semiconductor. Under zero-bias conditions, an excitation laser focused in the center of the opening will photogenerate a packet of electron–hole pairs. The resulting photoluminescence (PL) spot due to recombination will appear through the top surface roughly in the same location as the focus of the laser [Fig. 1(a)]. However, applying a bias voltage between the two electrodes will create an electric field that will accelerate the electrons to a velocity $v_d = \mu_n E$, where E is the lateral electric field intensity and μ_n is the electron mobility. While the bias is applied, the electrons will continue to drift from their generation position toward the positive electrode until they eventually recombine with a hole. This results in an overall shift of the excess minority carrier distribution toward the positive contact. If a majority of the electrons are transported under the electrode before they recombine, the contact shadowing will effectively block the external light emission [Fig. 1(b)]. If the internal electric field due to the applied voltage is large enough, the drifting and shadowing process can result in a faster extinction of the light emission than the typical decay due to the minority carrier lifetime. When the applied voltage is returned to zero, the external PL emission intensity in the photopumped region will rapidly increase in time as a function of the minority carrier lifetime. Therefore, a fast optical falling edge can be generated by rapidly removing photogenerated carriers from the optical exit aperture with a fast electrical pulse.

A second modulation technique is also being considered

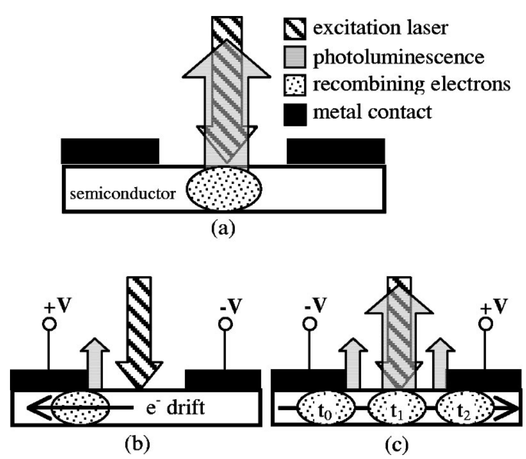

FIG. 1. Cross-sectional view of FAST concept. Black arrows point in the direction of the electron drift. Laser excitation and PL emission (a) under zero bias, (b) contact shadowing and attenuation of external PL emission under dc bias, and (c) transient response ($t_0 < t_1 < t_2$) of PL emission and optical pulse generation due to a switch in applied bias polarity.

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that utilizes a differential applied voltage and the carrier storage during the shadowing process to create the external light pulse. When the polarity of the voltage is switched, the electron drift will reverse directions and begin to flow toward the opposite contact. The electrons that were shadowed by the first contact and have not yet recombined can now drift underneath the aperture opening, and the PL emission due to this packet will once again be allowed to transmit through the surface [Fig. 1(c)]. Naturally, the light will be blocked again once the majority of the recombining electrons drift under the second contact This drifting and shadowing process will result in an external burst of light for the period of time that the recombining packet is positioned within the window region. An interesting attribute of this technique is that it requires only a fast differential rising or falling electrical edge (e.g., $+V \rightarrow -V$) to generate the light pulse rather than a short return-to-zero single ended electrical pulse. Additionally, the rising edge of the light pulse is now a function of the carrier drift velocity rather than the recombination lifetime. This characteristic may potentially result in shorter PL emission rise times than those produced by the single ended voltage technique. In GaAs, the saturation drift velocity is in excess of 1×10^7 cm/s. One can then conclude that if the concept were employed at this velocity with a 5 μm wide aperture opening, the external light pulse generated would be approximately 100 ps. This would suggest possible device operation on a time scale consistent with 10 Gbit/s operation.

Test structures were fabricated from solid-source molecular beam epitaxy (MBE)-grown $Al_{.90}Ga_{.10}As/GaAs/Al_{.90}Ga_{.10}As$ double heterostructures. The top and bottom $Al_{.90}Ga_{.10}As$ barrier layers were 25 and 50 nm thick, respectively, and were incorporated to reduce surface recombination effects and confine the photogenerated electrons within a 100 nm *p*-type GaAs active layer. The AlGaAs layers were heavily doped *p* type with beryllium to $N_A = 2\times10^{19}$ cm^{-3} with the intention of modulation *p* doping the GaAs layer to the mid-1×10^{18} cm^{-3}. The use of modulation doping was employed to help maintain high electron mobility within the GaAs active layer. The minority carrier lifetime of the active layer was measured with time resolved PL to be 870 ps. Consequently, a lifetime this short facilitates in maintaining a compact electron packet by reducing carrier diffusion. Additionally, 50 nm of $Al_{.50}Ga_{.50}As$ along with a 10 nm GaAs capping layer were grown on top of the structure to reduce surface oxidation. Large Al compositions ($\geqslant$50%) were employed to reduce absorption of the pump laser light in the cladding regions as well as to increase the valence-band offset to GaAs to enhance the modulation doping. van der Pauw mesa structures were etched into the wafer and Ti:Au nonalloyed electrical contacts were deposited and lithographically defined on top of the mesas. The central opening in the van der Pauw patterns were approximately 100 μm in diameter. The symmetric contact arrangement and the clear central region in the van der Pauw formed an aperture ideal for observing the effects of the lateral electric field on the PL emission. A diode laser was focused to a spot in the center of the van der Pauw for the photogeneration of electrons (diameter$<$100 μm, $\lambda = 660$ nm, and $P_{pump} = 9.3$ mW).

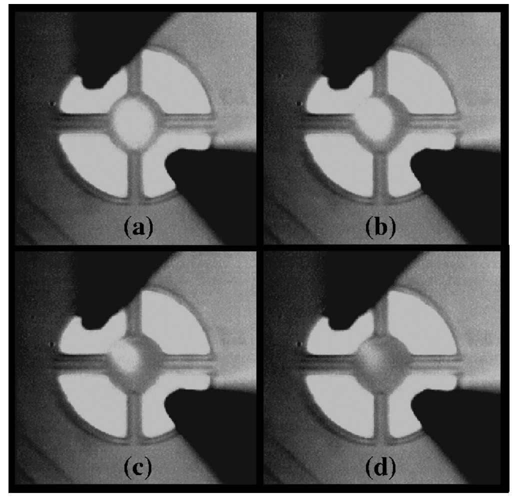

FIG. 2. Spatial modulation and contact shadowing of PL emission for different applied bias voltages. The bias was applied to the electrical probes visible on the top left- and lower right-hand side contacts. (a) Zero bias, (b) 2.5 V, (c) 10 V, and (d) 20 V. For all four conditions, the excitation laser is focused in the center of the structure.

Images were taken with a silicon complementary metal–oxide-semiconductor microscope camera of the PL emission spot ($\lambda_{center} \sim 870$ nm) transmitted from the surface of the semiconductor [Fig. 2]. A colored glass filter was used to remove the excitation laser light from the images. When a bias voltage was applied to the electrodes, the PL emission spot was swept toward the positive voltage terminal [Figs. 2(b) and 2(c)]. As this voltage was increased, the PL spatial displacement continued to increase until it appeared to be almost swept completely under the positive electrode [Fig. 2(d)]. When a slowly varying voltage ramp was applied to the electrodes (40 V p-p, $<$1 Hz), the PL spot scanned back and forth smoothly between the two contacts, while the pump laser stayed stationary, focused in the center of the structure. Clearly, electron drift prior to recombination is the source of this PL displacement. On average, this displacement should be equal to the distance that the electrons drift from their generation position in the recombination lifetime τ. As a first-order approximation, the distance d that the electrons drift from their generation position is $d = \mu_n E \tau$. For the *p*-GaAs epitaxial structure presented in this study, $\tau \sim 870\times10^{-12}$ s, $\mu_n \sim 2000$ cm^2/V s, and $E_{max} = 2000$ V/cm. Therefore, the calculated average distance a photogenerated electron would drift is approximately 35 μm. This first-order approximation appears to be in reasonably good agreement with the observed behavior [Fig. 2(d)].

To investigate the utility of this concept for modulating the intensity of optical emitters, the PL spectral intensity profile was measured as a function of the applied voltage. The external pump laser was replaced in this measurement with a fiber pump/probe apparatus [Fig. 3]. This procedure insured that the collected PL emission was centered directly over the photogeneration region and precluded any shadowing of the pump source by the probe. The core of a single mode 5 μm diameter fiber was placed in direct contact with the center of the van der Pauw structure. A fiber splitter/combiner was integrated into the measurement setup to connect a fiber pigtailed pump laser to the probe. A U bench with a colored glass filter removed the laser emission from the spectrum

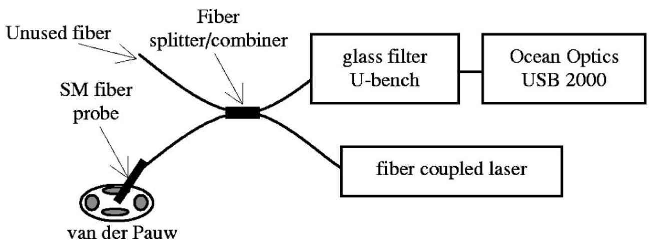

FIG. 3. Pump–probe setup for spectral intensity vs voltage measurement.

and, an Oceanoptics USB 2000 fiber coupled optical spectrometer measured the PL spectral response. Note that in the experiment discussed previously, the metal contacts were used to create the aperture mask to attenuate the optical emission. In this measurement the fiber probe itself functions as the exit aperture. Thus, as the fiber laser pumped the sample in a single spot, the collected PL intensity could be modulated by sweeping the packet from under the fiber core.

The spectral response was recorded for several dc bias voltages between 0–15 V, and the relative PL intensity was significantly reduced as the bias voltage increased [Fig. 4]. Although this is only a relative measurement, the observation suggests that the selectable aperture action can easily reduce the emission intensity by nearly an order of magnitude. Notice that the attenuation effects between 2.5 V and 5 V appear to be nonlinear, but at higher applied voltages a more linear relationship exists. The explanation for this phenomenon becomes clear when the current versus voltage ($I-V$) characteristics for the structure are examined [Fig. 5]. Note that at lower voltages, there exists a slight nonlinear $I-V$ consistent with back-to-back Schottky diodes. This behavior is not surprising for nonalloyed metal contacts to p-type AlGaAs. The slightly nonlinear $I-V$ should be directly related to the minority carrier current. This would reduce the sweeping velocity and explain the nonlinear emission intensity versus voltage observed at lower biases. However, once the Schottkys are fully rectifying the structures, $I-V$ behavior becomes very linear and exhibits a resistive behavior. Likewise, the PL quenching effect appears to operate more linearly in this region. However, absolute power measurements to quantify this completely are planned for future work.

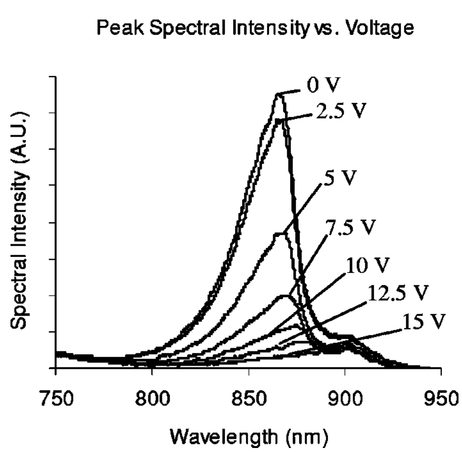

FIG. 4. Spectral intensity of PL emission as a function of voltage. As the applied bias is increased, the emission intensity is reduced by aperture selecting transport. The shift in the peak intensity wavelength is most likely due to the Stark effect.

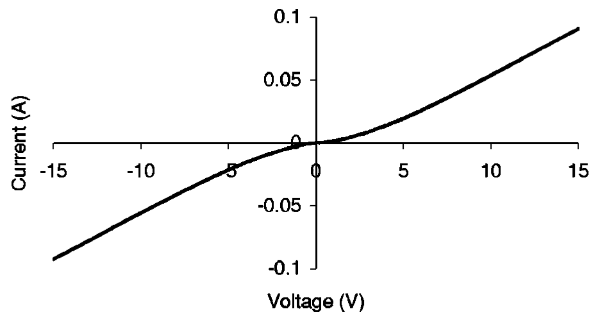

FIG. 5. Dark current vs voltage relationship for van der Pauw structures used to study the FAST concept. At low voltages, the slight nonlinear behavior suggest back-to-back Schottky diode characteristics. For larger voltages, the device appears linear and resistive.

Consistent with the Stark effect, a slight shift was observed in peak emission intensity to longer wavelengths as the bias voltage was increased. It is interesting to note that if the current structures are replaced with quantum wells, a magnification of this effect is expected, which may also have some interesting attributes for future emitters. Other potential categories of optoelectronic devices that could benefit from the ability to spatially relocate a luminescent carrier packet are optical signal routing devices and edge emitting routing devices. Since the displacement distance is fixed for a constant bias voltage (electric field), we intend to investigate the development of an optical signal routing device, excluding micromirror arrays, utilizing the FAST concept with pigtailed fibers aligned along the electron sweeping axis as well as cleaved facet edge emitting structures.

A modulation technique has been introduced that is potentially faster than current lifetime limited LED technologies. Initial experiments have demonstrated the ability to significantly attenuate the PL emission from an optically pumped semiconductor region, and scaling law arguments have been considered that suggest this technique may be suitable for high-speed applications. Additionally, the ability to spatially relocate the PL emission has been observed suggesting the possible optical signal routing applicability. The fundamental physics relating to the lateral transport of the excess minority carriers is currently under investigation. Future work will also include direct high-speed optical transient measurement as well as exploration of the engineering issues relating to high-speed device operation.

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