Light-emitting devices based on the real-space transfer of hot electrons

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The real-space transfer of hot electrons into semiconductor layers, where the transferred electrons are minority carriers, results in a generation of light by recombination. Based on this principle, several optoelectronic devices of varying degree of complexity are proposed in the present work. In particular, we propose a new class of vertical-cavity surface-emitting lasers that can be implemented in a number of heterostructures, including long wavelength materials (over 1.5 μm). An advantage of these structures is that the injection can be arranged without any current passing through the dielectric mirror stacks forming an optical cavity. Real-space transfer lasers can be used as logic devices with optical output functionally related to two or more electrical inputs.

The concept of real-space transfer[1] (RST) describes the process in which electrons in a narrow semiconductor layer, accelerated by an electric field parallel to the layer, acquire a high average energy (become "hot") and then spill over an energy barrier into the adjacent layer. This principle underlies the operation of a three-terminal hot-electron device, called the charge injection transistor or CHINT.[2,3] The basic structure of CHINT is illustrated in Fig. 1. The emitter is a conducting layer that has source and drain contacts and plays the role of a hot-electron cathode. The other conducting layer, the collector, is separated by a potential barrier. When the emitter electrons are heated by the source-drain field, most of them do not reach the drain but are injected over the barrier into the collector layer.

Charge injection by real-space transfer is very efficient. It can be considered analogous to the usual thermionic emission, but at a high effective electron temperature T_e. Even though only a small fraction of electrons in the high-energy tails of the hot-carrier distribution function participate in the RST, those tails are replenished at a fast rate, mainly determined by electron-electron collisions.

In all RST transistors demonstrated so far, the charge injection occurs between layers of the same conductivity type.[4] To my knowledge, injection of minority carriers by RST has not been contemplated, as this would be of no apparent advantage for transistor applications.[5] In contrast, the very essence of optoelectronic devices discussed below requires minority injection.

Figure 2 shows the cross section of a representative device structure and its energy-band diagram. Throughout our discussion InP-based heterostructures will be assumed. The lattice-matched $In_{0.53}Ga_{0.47}As$/InP system appears to be one of the better candidates for the implementation of this class of devices because of the proven excellent RST properties[6] of InGaAs on the one hand, and the large valence-band discontinuity[7] on the other. The latter is needed to suppress the injection of holes into the emitter layer.

In the absence of a heating field ($V_{SD} = 0$) the device is expected[7] to draw little current even under a substantial collector bias, as illustrated in Fig. 2(b). When an applied heating bias exceeds certain critical value $V_{cr}^{(1)}$, the drain characteristic shows negative differential resistance (NDR) and a high-field domain is formed in the emitter channel.[8] The value of $V_{cr}^{(1)}$ depends on the emitter channel length and the barrier height for charge injection. For a 1 μm channel in InGaAs/InP heterostructures one can expect $V_{cr}^{(1)} < 0.5$ V perhaps even as low as 0.25 V.[9] Further increasing V_{SD} leads to a rapid rise in the injection current. Measurements in this range are difficult because of instabilities driven by the NDR in the drain circuit. Finally, when V_{SD} exceeds another critical value $V_{cr}^{(2)}$, the NDR regime ends and the device becomes stable. At this point, most of the source current is injected over the barrier. In InGaAs/InAlAs devices,[6] the ratio J_C/J_D can exceed 10^4 (here J_C and J_D are, respectively, the linear densities of the collector and the drain currents per unit width of the emitter). The maximum injection current density can be estimated from the known dielectric strength E_{br} of the barrier:

$$J_C^{max} = \epsilon E_{br} v, \tag{1}$$

where ϵ is the barrier permittivity and v an effective high-field electron velocity in the emitter channel prior to RST. Taking $\epsilon E_{br}/e \approx 10^{12}$ cm^{-2} and assuming the peak

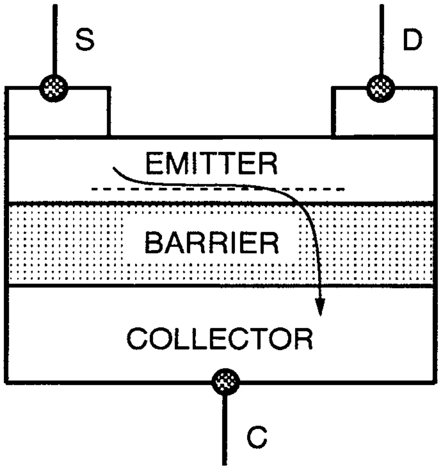

FIG. 1. Schematic diagram of a charge-injection transistor. The arrow shows the direction of electron flow.

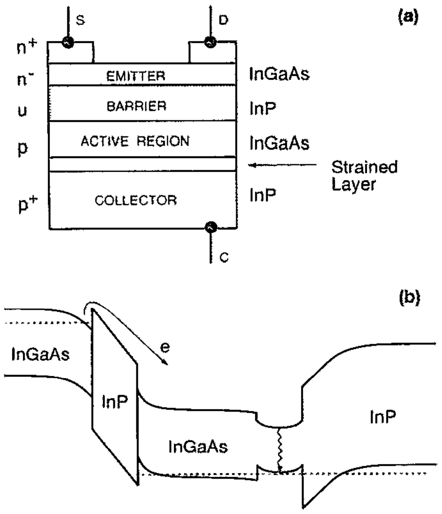

FIG. 2. Illustration of the generic structure of light-emitting devices based on charge injection. (a) Layer sequence and the arrangement of controlling electrodes. The strained layer represents an optical narrow $(\mathrm{In}_{1-x}\mathrm{Ga}_x)\mathrm{As}$ sublayer of the active region, with a lower Ga content, $x<0.47$, designed so as to emit at a wavelength longer than the fundamental absorption threshold in the lattice-matched InGaAs layers. (b) Band diagram in a cross section of the device in the emitter region. The diagram correponds to a positive bias on the collector in the absence of a heating source-to-drain field.

scattering-limited velocity $v \approx 2\times 10^7$ cm/s for channel electrons,[10] we find $J_C^{\max} \approx 3$ A/cm.[11] The dependence of $J_C^{\max}$ on the channel length is weak because most of the injection occurs in a narrow domain.

The injected minority carriers recombine in the active region producing luminescence at the fundamental wavelength of the active material (1.65 μm for $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$). Due to the peculiar symmetry[12] of charge injection by RST, such light-emitting devices can be useful as logic elements transforming electrical inputs into an optical output. This symmetry, expressed by the fact that the RST current does not depend on which of the two surface terminals, S or D, is chosen to be the source, allows the implementation of devices in which the role of a particular terminal in the circuit is not defined by the layout. For example, for a fixed collector bias, the device in Fig. 2 acts as an exclusive OR gate:

$$L = \mathrm{XOR}(S,D), \tag{2}$$

where S and D represent digital binary (high, low) voltage signals on the S and the D electrodes, respectively, and L is a binary output light signal.

The longer wavelength sublayer, "optionally" inserted in the active region (Fig. 2), may not be necessary unless one is interested in a coherent light source. To implement a semiconductor laser based on charge injection, the loss budget is of paramount importance, and it may be desirable that the emitted photon energy be lower than the fundamental absorption threshold in the emitter layer. In the InGaAs/InP heterostructure this can be achieved by using a strained layer of $(\mathrm{In}_{1-x}\mathrm{Ga}_x)\mathrm{As}$ with $x<0.47$ in the active collector region. Alternatively, one can use an emitter layer with slightly wider band gap than that in the optically active region.

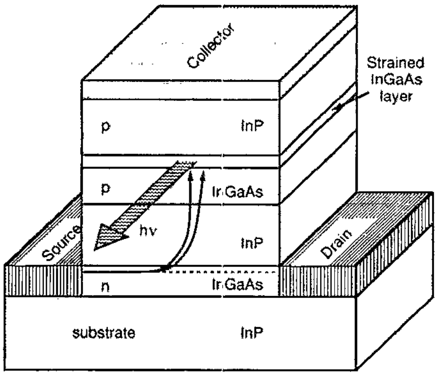

FIG. 3. Schematic diagram of a top-collector charge injection laser. Solid arrows indicate the direction of RST.

The design of a guided wave edge-emitting charge-injection laser is relatively straightforward; for this purpose it may be advantageous to employ structures with the collector on the top, as illustrated in Fig. 3. Recently, reported top-collector unipolar RST transistors show excellent microwave performance.[13]

Perhaps the most interesting possible application of the minority-carrier injection by RST is to the implementation of vertical-cavity surface-emitting lasers (SELs). The SELs are currently under intensive development for use in lightwave communication and optoelectronics.[14] A possible charge-injection surface-emitting laser structure is shown in Fig. 4.

In this structure the optical cavity is formed by two mirrors that represent quarter-wave stacks of dielectric pairs. Recently, Deppe *et al.*[15] demonstrated an excellent reflectivity in the wavelength range 1.5–1.8 μm with mirrors formed by four $\mathrm{Si/SiO_2}$ pairs, electron beam evaporated on InP substrate at low temperatures. Lateral con-

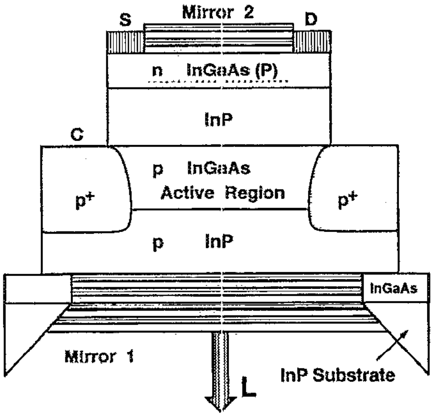

FIG. 4. Vertical-cavity surface-emitting charge-injection laser. Mirrors 1 and 2 are quarter-wave dielectric stacks. The bottom InGaAs layer is an etch stop for the removal of InP substrate prior to the deposition of mirror 1. The total cavity length is about 1 μm. To minimize absorption loss in the emitter channel the latter can be implemented in a lattice-matched InGaAsP material or as a strained $(\mathrm{In}_{1-x}\mathrm{Ga}_x)\mathrm{As}$ layer with $x>0.47$.

finement of injected electrons in the active layer can be provided by an implantation or diffusion of acceptors, as illustrated in Fig. 4. Prior to the deposition of mirror 1, the InP substrate can be etched away by V-groove techniques, stopping at a specially inserted InGaAs layer. The latter may then also be etched away by another solvent.

In a vertical resonator, the strained-layer scheme of Fig. 2 for the active layer may not be feasible, because the thickness d of a strained layer is limited by the conditions of pseudomorphic growth. Given that the active medium gain g_{th} at the threshold, typically, does not exceed 500 cm^{-1}, the required d of order 1 μm would be difficult to achieve. A less demanding approach to the implementation of a charge-injection SEL, is to keep a lattice-matched active layer but, if necessary, slightly enhance the band gap in the emitter region to minimize the absorption there, cf., Fig. 4.

The gain-loss budget in surface-emitting lasers is discussed in detail by Iga *et al.*[14] At the threshold, the optical loss for the resonant mode must balance the gain:

$$g_{\mathrm{th}}d_{\mathrm{ac}}=\alpha_{\mathrm{ac}}d_{\mathrm{ac}}+\alpha_{\mathrm{em}}d_{\mathrm{em}}+\alpha_{\mathrm{cl}}d_{\mathrm{cl}}+\mathrm{In}(R_1R_2)^{-1/2}+D, \tag{3}$$

where α_{ac}, α_{em}, and α_{cl} are the absorption coefficients in the active, emitter, and cladding layers of the thickness d_{ac}, d_{em}, and d_{cl}, respectively, D is the diffraction loss of the resonator, and R_1, R_2 are the mirror reflectivities. We can expect that InP layers of thickness $d_{\mathrm{cl}}\sim 100$ nm will contribute negligible losses; the lightly doped emitter layer of thickness $d_{\mathrm{em}}\leqslant 50$ nm should not be a problem either, especially if one uses a slightly higher band-gap material for this layer. The reported reflectivity of Si/SiO$_2$ mirrors 1.65 μm is better than 0.99, so that the reflection less should be less than 1%. Thus, we can anticipate that the main design trade-off is between the diffraction loss minimized by increasing the Fresnel number of the resonator, and the charge-injection efficiency, which decreases with increasing lateral dimensions.

It is reasonable to expect that in a device with optimized active region the total cavity length can be made as short as 1 μm. This means that we can have a resonator with a large Fresnel number (and a small diffraction loss) with the lateral dimensions of the active region of order 1 μm. The device can be expected to lase, provided sufficient current can be achieved by the RST process. If the RST injection is limited by Eq. (1), the areal current density for a 1 μm channel can be as high as 30 $\mathrm{kA/cm}^{-2}$. Still higher injection can be achieved with an avalanche multiplication[11] in the barrier, if the latter is sufficiently thick.

In conclusion, we have discussed several optoelectronic devices of varying degree of complexity, whose principle is based on the charge injection of minority carriers by the real-space transfer. An important advantage of all light-emitting devices discussed above is their logic functionally with respect to electrical input. With two emitter contacts, S and D, the optical output obeys Eq. (2). Moreover, it is possible to design a symmetric arrangement of *three* surface electrodes X_j ($j=1, 2, 3$) (in addition to the collector), each acting as a source or a drain terminal with respect to the other two electrodes. Such a device would be an optoelectronic analog to the NORAND element,[12] its optical output L being complementary to the logic value of NORAND's OUT signal, viz. $L=\overline{\mathrm{OUT}}$, where

$$\mathrm{OUT}(\{X_j\})=(X_1\cap X_2\cap X_3)\cup(\overline{X}_1\cap\overline{X}_2\cap\overline{X}_3), \tag{4}$$

and the symbols $\cap$, $\cup$, and $\overline{A}$ stand for logic functions AND, OR, and NOT A, respectively. This element, which may be termed "ORNAND", gives $L=\mathrm{OR}\ (X_1, X_2)$ when the input to X_3 is low, and $L=\mathrm{NAND}\ (X_1, X_2)$ when X_3 is high. In my opinion, such an element will find important optoelectronic applications.

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[1] K. Hess, Festkörperprobleme **25**, 321 (1985).

[2] S. Luryi and A. Kastalsky, Superlatt. Microstructures **1**, 389 (1985).

[3] References to the recent work on real-space transfer devices can be found in S. Luryi, Superlatt. Microstructures **8**, 395 (1990).

[4] Both the injection of electrons into n-type collector and that of holes into p-type collector have been demonstrated, cf., references cited in Ref. 3.

[5] Even in those applications the use of minority injection may be beneficial. One advantage may result from the ease of making closely spaced contacts of opposite polarity without introducing an unwelcome leakage between the emitter and the collector. Such considerations, however, have become less pressing after the successful development of epitaxial ohmic contacts to the emitter [P. M. Mensz, S. Luryi, A. Y. Cho, D. L. Sivco, and F. Ren, Appl. Phys. Lett. **56**, 2563 (1990)].

[6] P. M. Mensz, P. A. Garbinski, A. Y. Cho, D. L. Sivco, and S. Luryi, Appl. Phys. Lett. **57**, 2558 (1990).

[7] We assume the following room-temperature band offsets in the $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As/InP}$ system: $\Delta E_C=0.25$ eV and $\Delta E_V=0.35$ eV, cf., D. V. Lang, in *Heterojunction Band Discontinuities: Physics and Device Applications*, edited by F. Capasso and G. Margaritondo (Elsevier, Amsterdam, 1987), Chap. 9, and references cited therein.

[8] In principle, both the NDR and the domain formation can be entirely of the real-space transfer nature. In materials with low-lying satellite valleys, however, the momentum-space transfer effects may dominate over the RST [see I. C. Kizillyalli and K. Hess, J. Appl. Phys. **65**, 2005 (1989)]. Inasmuch as the satellite-valley separation in $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ ($\Delta E_{\Gamma L}\approx 0.55$ eV) much exceeds the barrier height ΔE_C for charge injection, it is safe to assume that the Gunn effect should play no role in the RST process in InGaAs/InP heterostructures.

[9] Based on preliminary measurements of RST in a unipolar $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As/InP}$ CHINT structure [R. S. Hamm, S. Luryi, P. M. Mensz, and M. B. Panish (unpublished, 1989)].

[10] M. A. Littlejohn, T. H. Glisson, and J. R. Hauser, in *GaInAsP Alloy Semiconductors*, edited by T. P. Pearsall (Wiley-Interscience, New York, 1982), Chap. 10.

[11] It should be noted that the highest measured values of J_C (over 10 A/cm) considerably exceed estimates based on Eq. (1). While it is possible that the transient electron velocity in the channel strongly overshoots the scattering-limited value, it is more likely that the measured values of J_C include an impact-ionization gain. Avalanche multiplication in the wide-gap barrier layer, initiated by the RST, may be beneficial for increasing the power of light-emitting devices proposed here.

[12] S. Luryi, P. M. Mensz, M. R. Pinto, P. A. Garbinski, A. Y. Cho, and D. L. Sivco, Appl. Phys. Lett. **57**, 1787 (1990).

[13] M. R. Hueschen, N. Moll, and A. Fischer-Colbrie, Appl. Phys. Lett. **57**, 386 (1990).

[14] K. Iga, F. Koyama, and S. Kinoshita, IEEE J. Quantum Electron. **QE-24**, 1845 (1988).

[15] D. G. Deppe, S. Singh, R. D. Dupuis, N. D. Gerrard, G. J. Zydzik, J. P. van der Ziel, C. A. Green, and C. J. Pinzone, Appl. Phys. Lett. **56**, 2172 (1990).