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InAs/GaSb-based lateral current injection laser

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We propose a contact structure for InAs/GaSb multilayers, such that electrons and holes are selectively injected in alternating layers. This enables the implementation of a far-infrared lateral current injection laser based on the InAs/GaSb superlattice. Preliminary calculation of the gain shows that both surface- and edge-emitting designs are possible. [DOI: 10.1063/1.1410888]

I. INTRODUCTION

Type-II heterostructures using the InAs/GaSb/AlSb family of materials are attractive for the implementation of mid-infrared semiconductor lasers because of their wide tunability and good carrier confinement. The type-II band structure suppresses a troublesome channel for Auger recombination, namely, that involving one conduction-band electron and two holes in the heavy-hole and the split-off valence bands.[1–3] In contrast to the more common type-I heterostructures, carrier bands of the constituent semiconductors in type-II heterostructures overlap, so that the top of the valence band in GaSb is 150 meV above the bottom of the conduction band in InAs. This overlap is removed when both materials are in the form of layers sufficiently narrow that the electron and hole quantum-confinement energies together exceed the overlap of bulk bands. Such confined structures offer a lasing transition from the first electron level (e1) in the InAs quantum well to the first heavy hole level (hh1) in the GaSb well. To increase the transition matrix element, pure InAs and GaSb can be replaced by compounds (e.g., GaInSb), thus increasing the wave-function overlap between the two wells. To reduce the strain induced by a lattice mismatch, one can use structures more complicated than a simple double quantum well.[2,4,5] The unit structures can be periodically repeated to form a superlattice with an extended optically active region. Such superlattices have sufficient gain to be used for vertical cavity surface emitting lasers (VCSELs), that can be pumped either optically[6–13] or electrically.[8,14,15] Edge-emitting lasers based on InAs/GaSb superlattices have also been demonstrated by a number of authors.[16–23] Similar structures have also been used for cascade lasers.[7,24–28]

An essential part of the active region in the type-II superlattice lasers is a highly resistive superlattice, which makes it difficult to design an electrically pumped structure without too much heat dissipation. In a sense, the problem is similar to that facing the designer of VCSELs, which commonly contain superlattices as Bragg-reflecting mirrors in the cladding region. The electrical impedance of such mirrors is a factor limiting the freedom of design. One way of alleviating this problem in VCSELs has been to use lateral electrode contacts to the top cladding layer.[29] This approach allows one to avoid passing current through the Bragg mirrors; however, it does not envision contacts to the active layer itself. One of the advantages, perhaps the major advantage of lateral injection for VCSEL, is that the mirror stack can be made of dielectric layers of vastly disparate refractive index, thus dramatically reducing the required thickness of the mirror stack. E.g., one can use just a few periods of SiO_2/Si_3N_4 or Si/SiO_2 (Ref. 30) instead of semiconductor superlattices where the index contrast is very small.

Dealing with the InAs/GaSb/AlSb family of materials, it is very attractive to implement lateral current injection in the active layer itself, which would make it possible to fully utilize the material advantages of type-II superlattices in electrically pumped laser designs. However, unlike the earlier cited case of a VCSEL, the lateral injection in the active region has to be performed selectively, i.e., electrons and holes must be injected in different layers, so that the radiative recombination could take place at all interfaces of the superlattice. Moreover, since a significant fraction of injected carriers may flow without recombination across the entire structure, a viable selective injection scheme must also block carriers from entering the opposite contact. Because of the absence of contacts providing selective injection, no combination of type-II heterostructure lasers with lateral injection has been contemplated.

In this article, we propose a method for implementing doped *n*- and *p*-type contacts to type-II superlattices, which provides selective injection of carriers into the interdigitated layers of the superlattice. The method makes use of the band offset between InAs and GaSb to block electrons from entering GaSb layers and holes from entering InAs layers of the superlattice. Thus, neither the hole nor the electron current can flow across the whole structure from one lateral contact to another and all injected carriers recombine in the multilayers. This offers a significant improvement in the performance of type-II semiconductor lasers. The use of a thick superlattice in the active region allows one to increase the lasing power proportionally to the superlattice thickness. The quantum-confinement energy can be used to tune the

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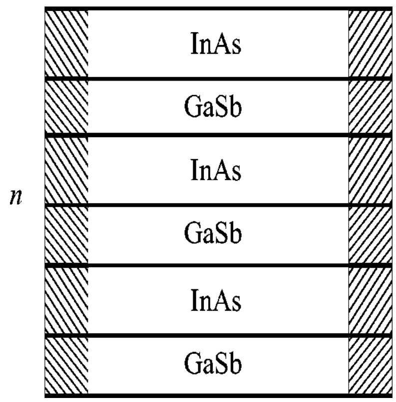

FIG. 1. InAs/GaSb superlattice. The shaded areas show doped regions of the superlattice for the n and the p contacts.

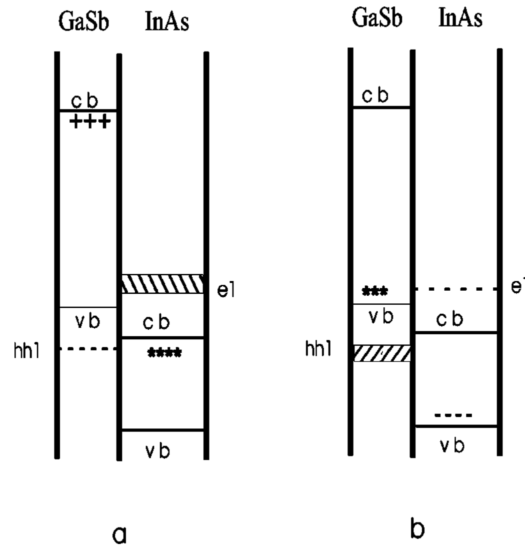

FIG. 2. Band structure of n (a) and p (b) contacts. The bottom of the conduction band and the top of the valence band are indicated by cb and vb, respectively, the ground-state electron and hole levels in InAs and GaSb wells by e1 and hh1, the levels of charged donors and acceptors by $+++$ and $---$, respectively, and the level of neutral impurities is shown by $***$. The shaded area above the e1 level in the InAs well shows the electron filling, and that below the hh1 level in the GaSb well shows the hole filling.

lasing wavelength in the range between approximately 1 and 40 μm.

For other material systems, semiconductor lasers with lateral injection have been discussed by a number of authors (see, e.g., Refs. 31–45). Efforts to develop lateral injection lasers have been mostly aimed at monolithic optoelectronic integration[46–48] since both contacts in these lasers can be put on the top surface. Other researchers have been motivated by design possibilities, such as adding functional features in the vertical direction, e.g., adding a third terminal for the purposes of gain switching, capacitive modulation, and gain tuning.[49–53] Lateral injection of carriers should be of particular importance for the implementation of vertical-cavity surface-emitting lasers, where it allows one to avoid passing the current through the Bragg mirrors.[29]

II. STRUCTURE

The structure shown in Fig. 1 comprises an InAs/GaSb superlattice with quantum wells so narrow that the quantum-confinement effect replaces the band overlap with a narrow gap. Two contact regions are arranged laterally, one doped with impurities of p type for both InAs and GaSb (Zn, Mn, Cd), the other with impurities of n type for both materials (Sn, Te). Both contacts can be fabricated, e.g., by ion implantation and subsequent annealing, a well-developed technology for both InAs and GaSb.[54–58] The p contact injects holes into GaSb layers, while the n contact injects electrons into InAs layers. Radiative recombination takes place at all interfaces between these layers. The threshold photon energy E_0 is given by $E_0 = E_{e1} + E_{hh1} - 150\,\text{meV}$.

Both energies E_{e1} and E_{hh1} are limited by the confining barriers for electrons in InAs quantum wells and holes in GaSb quantum wells, respectively. This limitation makes the selective injection effective only in the mid- and far-infrared region.

The band structures of the n- and p-type contacts are shown in Figs. 2(a) and 2(b), respectively. In the n-type contact, all donors in GaSb wells are ionized, producing electrons in InAs wells. Similarly, in the p-type contact, all acceptors in InAs wells are ionized with holes residing in GaSb wells. The ratio of the minority-carrier concentration n_2 in the contact to the majority-carrier concentration n_1 is given by

$$\frac{n_2}{n_1} = \frac{m_2 k_B T}{\pi \hbar^2 n_1} \ln[1 + e^{-\Delta_{12}/k_B T}(e^{\pi\hbar^2 n_1/m_1 k_B T} - 1)^{-1}], \tag{2.1}$$

where m_1 and m_2 are masses of the majority and minority carriers, respectively. The barrier for minority carriers equals the threshold energy, $\Delta_{12} = E_0$. In the numerical estimates below, we take $m_e^{\text{InAs}} = 0.023$ for the electron effective mass. The in-plane hole masses are substantially affected by the size quantization and are smaller than the bulk masses.[59–63] In the "pocket" where the hh1 dispersion law applies, they are $m_{\text{hh}}^{\text{InAs}} = 0.04$ and $m_{\text{hh}}^{\text{GaSb}} = 0.08$. We can use these values so long as the characteristic hole wave vector is inside the pocket, i.e., is not large compared to $\approx 2/L$, where L is the width of the well. This condition is satisfied for the sheet concentration $10^{12}\,\text{cm}^{-2}$ and well widths less than 10 nm. For the calculation of the quantization energy in the GaSb well we use the bulk heavy-hole mass, $m_{\text{hh}\perp}^{\text{GaSb}} = 0.27$. The barriers confining electrons in InAs wells between GaSb layers are 0.85 eV and the barriers confining holes in GaSb wells between InAs layers are 0.51 eV. For a structure with 6 nm InAs wells and 3 nm GaSb wells we obtain the quantization energies $E_{e1} = 174$ meV and $E_{hh1} = 79$ meV. Using these values in Eq. (2.1) for an exemplary majority concentration $n_1 = 10^{12}\,\text{cm}^{-2}$ we find that the ratio n_2/n_1 is small even at relatively high temperatures, e.g., $n_2/n_1 \sim 0.05$ at 350 K.

The contacts are selective with respect to the injection of carriers into wrong wells. This means that both the concentration of electrons in GaSb wells at the n contact and the concentration of holes in InAs wells at the p contact are

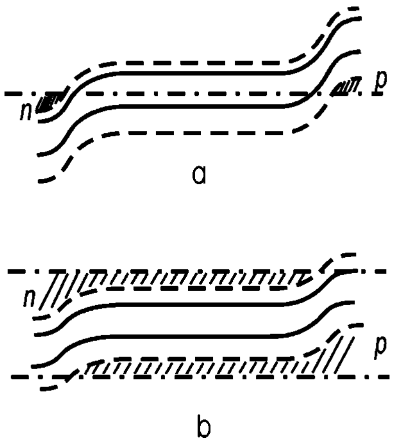

FIG. 3. Band bending and the carrier distribution along the layers of the superlattice. Letters n and p show the contacts, solid lines are the bottom of the conduction band and the top of the valence band, the dashed lines are the e1 and hh1 levels, dashed area shows energy regions filled with carriers. (a) Equilibrium, no voltage is applied. Dot-dashed line is the Fermi level. (b) Operating regime. Dot-dashed lines show the quasi-Fermi levels of electrons and holes.

small. Quantitatively, the selectivity can be defined as the ratio of the majority-carrier concentration in a wrong well n_1' to the total concentration n_1. It can be found from the expression

$$\frac{n_1'}{n_1}=\frac{m_{1'}T}{\pi\hbar^2 n_1}\ln[1+(e^{\pi\hbar^2 n_1/m_1 T}-1)e^{-\Delta_{11'}/T}], \qquad (2.2)$$

where $m_{1'}$ is the effective mass of the majority carriers in the wrong well. The barrier confining electrons in an InAs well is $\Delta_{11'}^{n}=0.85\,\mathrm{eV}\text{-}E_{e1}$, and the barrier confining holes in a GaSb well is $\Delta_{11'}^{p}=0.51\,\mathrm{eV}\text{-}E_{hh1}$. For our exemplary structure with 6 nm InAs wells and 3 nm GaSb wells Eq. (2.2) gives a better than 10^{-5} selectivity at $T=350\,\mathrm{K}$.

Figure 3(a) shows the band bending and the Fermi level across the whole structure without an applied voltage and Fig. 3(b) shows the band bending and the quasi-Fermi levels of electrons and holes for the operating regime. An applied voltage reduces the contact barriers, and hence, diminishes the selectivity of injection. To avoid a substantial degradation of the laser efficiency, the doping of both contacts must be quite heavy. If the areal concentration in the active region is $10^{12}\,\mathrm{cm}^{-2}$, the height of the contact barrier must be at least 30 meV. This requires a minimum sheet concentration in the contacts of about $10^{13}\,\mathrm{cm}^{-2}$, which corresponds to a volume carrier concentration of about $10^{19}\,\mathrm{cm}^{-3}$. These high doping levels are achievable in both InAs and GaSb.[57,64–67]

III. GAIN

We calculate the gain with the help of the expression

$$g=g_0[f_e(\epsilon_{e\omega})+f_h(\epsilon_{h\omega})-1]\,\theta(\hbar\omega-E_0), \qquad (3.1)$$

where $f_e(\epsilon)$ and $f_h(\epsilon)$ are, respectively, the electron and hole Fermi functions, $\epsilon_{e\omega}=(\hbar\omega-E_0)m_{\mathrm{hh}}^{\mathrm{GaSb}}/(m_e^{\mathrm{InAs}}+m_{\mathrm{hh}}^{\mathrm{GaSb}})$ and $\epsilon_{h\omega}=(\hbar\omega-E_0)m_e^{\mathrm{InAs}}/(m_e^{\mathrm{InAs}}+m_{\mathrm{hh}}^{\mathrm{GaSb}})$ are the electron and hole energies of the recombining pair, and $\theta(x)$ is the step function.

TABLE I. The lasing wavelength and gain for a surface-emitting laser in a few heterostructures.

L_{GaSb} (nm)	L_{InAs} (nm)	λ (μm)	g_0 (cm^{-1})
1.8	6.6	8.4	2300
1.8	8.4	12.	1720
2.4	6.6	11.6	2560
2.4	7.8	16.5	2300
3.0	7.2	19.	2620

The smearing of the energy spectrum of electrons and holes due to scattering is neglected in Eq. (3.1) (cf. Ref. 4). In addition to the spectrum smearing, scattering processes also change the entire expression for the transition probability and a consistent inclusion of these corrections requires two-particle Green functions.

The maximum value of the gain is

$$g_0=\frac{e^2}{m_0^2\omega}\,\frac{1}{n_{\mathrm{eff}}cL}\,\frac{2\pi m_e^{\mathrm{InAs}}m_{hh}^{GaSb}}{\hbar^2(m_e^{\mathrm{InAs}}+m_{\mathrm{hh}}^{\mathrm{GaSb}})}|M|^2, \qquad (3.2)$$

where m_0 is the free electron mass, $L=L_{\mathrm{InAs}}+L_{\mathrm{GaSb}}$ is the period of the InAs/GaSb superlattice, and $n_{\mathrm{eff}}=[(n_{\mathrm{InAs}}^2L_{\mathrm{InAs}}+n_{\mathrm{GaSb}}^2L_{\mathrm{GaSb}})/L]^{1/2}$ is the effective refraction index.

There are three channels for radiative transition at the InAs/GaSb interface: (i) electrons from InAs can virtually tunnel to the conduction band of GaSb and then recombine with holes; (ii) holes from GaSb can virtually tunnel to the valence band of InAs and then recombine with electrons; and (iii) electrons and holes can recombine directly due to the mixing of the conduction band of InAs with the valence band of GaSb at the interface. The latter mechanism can be neglected compared to the former two[68] and the transition matrix element reduces to

$$M=M_{\mathrm{env}}^{\mathrm{InAs}}p_{\mathrm{cv}}^{\mathrm{InAs}}+M_{\mathrm{env}}^{\mathrm{GaSb}}p_{\mathrm{cv}}^{\mathrm{GaSb}}, \qquad (3.3)$$

where $M_{\mathrm{env}}^{\mathrm{InAs}}$ and $M_{\mathrm{env}}^{\mathrm{GaSb}}$ are the matrix elements of the envelope wave functions in the InAs and GaSb well, respectively, while $p_{\mathrm{cv}}^{\mathrm{InAs}}$ and $p_{\mathrm{cv}}^{\mathrm{GaSb}}$ and the momentum matrix elements of the Bloch functions between the valence and conduction bands. The latter are usually expressed in the form $p_{\mathrm{cv}}=\sqrt{E_p m_0/2}$.[69] Experimental values for the energy E_p are $E_{\mathrm{p}}^{\mathrm{InAs}}=21.11\,\mathrm{eV}$ and $E_p^{\mathrm{GaSb}}=22.88\,\mathrm{eV}$.

Table I presents the calculated values of the lasing wavelength and the gain g_0 for a surface-emitting laser in several exemplary heterostructures. For the case of edge-emitting lasers the gain is reduced by the confinement factor. A typical temperature dependence of the gain is shown in Fig. 4.

The most important contribution to the loss due to free-carrier absorption comes from the lh1–hh1 transition. This transition, however, is suppressed because the Bloch functions in both levels have the same total angular momentum and the dipole matrix element between them vanishes. A nonzero contribution to this transition results from the dipole matrix element between the envelope functions, which is very small. According to our calculation, this rate of absorption is at least one or two orders of magnitude lower than g_0.

The relevant Auger recombination, e1–hh1 accompanied by the hh1–lh1 transition, is also strongly suppressed. The

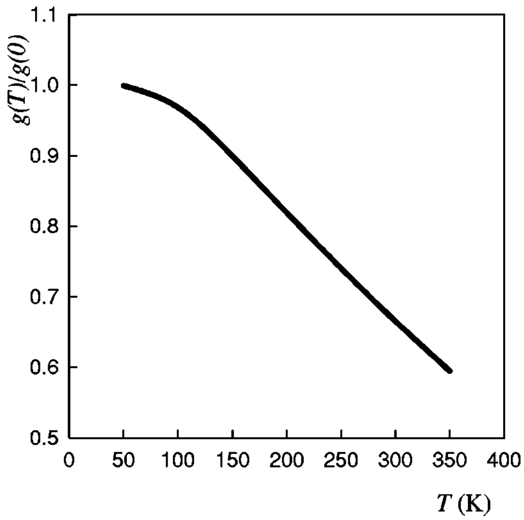

FIG. 4. Temperature dependence of the gain for the carrier concentration in the active region $10^{12}\,\mathrm{cm}^{-2}$.

reason is that the Bloch functions of hh1 and lh1 levels have different angular momentum projections on the z axis, so the matrix element of the Coulomb energy between these functions is very small. Calculation of the level energies shows that except for the structures in the first and the third lines in Table I this path of recombination is strongly suppressed even at room temperature. For the two exceptional cases it is suppressed at 77 K.

Another mechanism of loss results from the penetration of the electric field of the optical wave into the contacts. The field is polarized normally to the contact interfaces and creates an oscillating screening layer in them. When the contacts are heavily doped ($10^{19}\,\mathrm{cm}^{-3}$) the Maxwell relaxation time τ_M there is so short that $\omega\tau_M \ll 1$, where ω is the light frequency. In this limit the loss is proportional to $(\omega\tau_M)^2$, and hence, is also strongly suppressed.

IV. CONCLUSION

This article suggests a way of implementing lateral current injection lasers based on type-II heterostructures. Carriers are injected selectively, electrons into InAs wells from n contacts and holes into GaSb wells from p contacts. For surface-emitting lasers our design eliminates the necessity to fabricate Bragg-reflection mirrors of low resistivity. The same appoach may also be advantageous for edge-emitting lasers, where it alleviates the problem of heat dissipation in the active region. Our design appears promising in the range of 10–30 μm. The material gain in this region is larger than $2000\,\mathrm{cm}^{-1}$.

It is worthwhile to note that the proposed InAs/GaSb superlattice is only an example. The same design can incorporate more complicated superlattice structures that have been proposed to reduce strain resulting from the lattice mismatch (see, e.g., Refs. 4 and 5).

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