GaAs sawtooth superlattice laser emitting at wavelengths $\lambda > 0.9\ \mu m$

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A new type of semiconductor superlattice laser grown by molecular beam epitaxy is realized in GaAs. The active region of the injection laser consists of alternating *n* and *p* Dirac-delta doped layers resulting in a sawtooth-shaped conduction-band and valence-band edge. The band gap of this new GaAs superlattice is smaller than the GaAs bulk band gap. Room-temperature operation of broad-area GaAs sawtooth superlattice (STS) injection lasers is demonstrated at a wavelength of 905 nm. The threshold current density of the STS laser is 2.2 kA/cm^2.

The information carrying capacity of optical communication systems is in principle some orders of magnitude higher than the capacity of conventional electrical microwave transmission lines, due to the high carrier frequency exceeding 100 THz in optical systems as compared to frequencies smaller than 100 GHz in electronic microwave systems. The advantage of the low-loss wavelength region of silica fibres at $0.7\ \mu m \leqslant \lambda \leqslant 2\ \mu m$, where Rayleigh scattering and infrared absorption of molecules are small, is fully taken in wavelength-multiplexing systems. In such systems several lasers of different wavelengths emit into one single fiber at the same time. Therefore, semiconductor injection lasers with designable emission wavelengths are needed in the entire low-loss wavelength range of silica fibers. Double heterostructure lasers having a good optical confinement and emitting at wavelengths $\lambda < 0.89\ \mu m$ can be obtained from the material system $Al_xGa_{1-x}As/GaAs$.[1] Injection lasers which emit at wavelengths $\lambda > 1.1\ \mu m$ are obtained from the ternary material system $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ grown on InP[2,3] and the quaternary system $Ga_xIn_{1-x}P_yAs_{1-y}$ grown on InP.[4] An extension of the laser wavelength beyond $0.87\ \mu m$ by incorporation of In in the active layer of a $GaAs/Al_xGa_{1-x}As$ laser was demonstrated by Tsang.[5]

In this letter we present a new type of semiconductor *superlattice laser* which emits monochromatic and coherent radiation at wavelengths $\lambda > 0.9\ \mu m$. The interesting properties of the diode originate from the active layer consisting of alternating *n*- and *p*-doped regions of delta function like profiles in an otherwise homogeneous GaAs host material. In Fig. 1(a) we show the doping profile of the GaAs superlattice active region and of the adjacent homogeneously *n*-doped and *p*-doped $Al_xGa_{1-x}As$ confinement layers. The optical confinement layers are homogeneously doped in the 10^{17} cm^{-3} range as in a conventional double heterostructure laser. The doping profile of the active region (thickness $0.2\ \mu m$) consists of a periodic train of delta functions

$$N_D - N_A = N_D^{2D} \sum_{i=0}^{n} \delta(z - iz_p) - N_A^{2D} \sum_{i=0}^{n} \delta\left[z - \left(i + \frac{1}{2}\right) z_p\right], \quad (1)$$

where $z_p (= 20\ \text{nm})$ is the spatial period of the superlattice and N_D^{2D} or $N_A^{2D} (= 5 \times 10^{12}\ \text{cm}^{-2})$ are the two-dimensional donor and acceptor concentrations, respectively. The delta function like doping profiles are obtained by molecular beam epitaxy (MBE) in the *impurity growth mode*,[6] where the group-III element (Ga) shutter is closed while the shutter of the dopant and of the group-V element (As) effusion cell is kept open. Physically a delta function like doping profile means an impurity localization within *one single* group-III lattice plane of the GaAs zincblende structure grown on the polar (100) face. A sawtooth-shaped conduction and valence-band edge potential results from the charge distribution of Fig. 1(a) as calculated by a twofold integration of Poisson's equation.[6] The band diagram of the diode active layer is shown in Fig. 1(b) at zero applied voltage. The superlattice region is depleted from free carriers. Application of forward bias to the diode [Fig. 1(c)] flattens the bands resulting in electron and hole injection into the superlattice region. The subband energies in the V-shaped potential wells of the sawtooth superlattice have been presented elsewhere.[6,7] For efficient carrier injection, the forward threshold voltage V is equal to the superlattice band-gap energy E_g^{SL} divided by the elementary charge q, i.e., $V = E_g^{SL}/q = \hbar\omega/q = \phi_n - \phi_p$, where $\hbar\omega$ is the photon energy and ϕ_n and ϕ_p are the quasi-Fermi levels. Figure 1(c) shows that radiative electron-hole

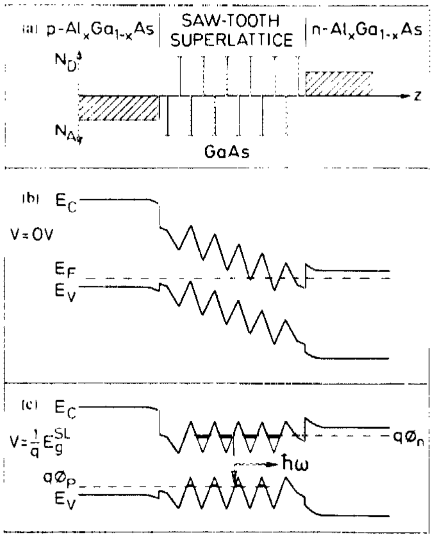

FIG. 1. Doping concentration and real-space energy band diagram of the sawtooth superlattice laser diode (not drawn to scale). (a) Dopant concentration of homogeneously doped $Al_xGa_{1-x}As$ confinement layers and of the Dirac-delta doped GaAs active region. (b) Sawtooth-shaped band diagram of the active layer and the adjacent confinement layers at zero bias. (c) Band diagram of the sawtooth superlattice laser at a forward bias of $V \simeq E_g^{SL}/q = \phi_n - \phi_p$.

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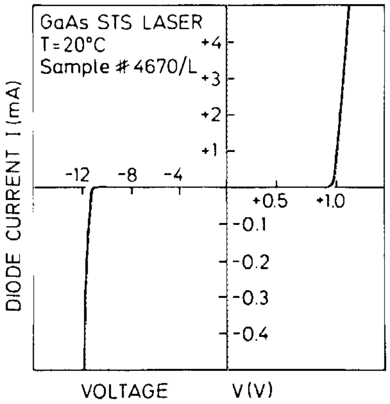

FIG. 2. Current-voltage characteristic of the sawtooth superlattice laser diode with a threshold voltage of $V_{th} \simeq 1$ V and a reverse breakdown voltage of $V_b = -11.5$ V.

recombinations occur in the high-purity undoped GaAs region between the *n*-type and *p*-type doped planes. Tail states which are expected in highly doped semiconductors do not exist in this intrinsic region.

The layer sequence of the new laser structure [Fig. 1(a)] with a p^+-GaAs cap layer is grown by molecular beam epitaxy and the GaAs substrate is then thinned to 150 μm. Ohmic contacts are obtained by Cr/Au and AuGe/Ni metallization for the *p* and *n* contacts, respectively. The samples are cleaved into pieces of $250 \times 250\,\mu\text{m}^2$ area and mounted on a Cu sample holder. The diodes are excited with a pulse generator giving 750-ns pulses at a repetition rate of 300 Hz. The electroluminescence of the devices is measured by an S1 photomultiplier attached to a 1-m single-pass monochromator.

The *n*-type and *p*-type delta function doped regions of the sawtooth superlattice (STS) do *not* act as isolated *p-n* junctions. Isolated *p-n* junctions would exhibit a blocking characteristic. Instead, the active layer has a *superlattice character*, i.e., it behaves like a homogeneous material. This fact is clearly demonstrated in the current-voltage (*I-V*) characteristic of the diode shown in Fig. 2. The forward threshold voltage of 1 V corresponds approximately to the STS band-gap energy E_g^{SL} divided by the elementary charge. This threshold voltage is lower as compared to the 1.4 V of regular double heterostructure lasers with uniform GaAs active layers. The value of E_g^{SL} depends on the design parameters of the superlattice.[6] The observed low threshold voltage of the diode indicates that tunneling through the narrow triangular barriers [see Fig. 1(c)] is the effective transport mechanism of carriers in the active layer of the laser. The *I-V* characteristic of the laser diode shows an extremely small leakage current in reverse direction ($< 1\,\mu$A) and a large breakdown voltage of -11.5 V, indicating the high quality of the diodes.

In Fig. 3 the spontaneous and stimulated emission spectra of the GaAs STS laser measured at room temperature (20 °C) are presented. For current densities smaller than the threshold current density ($I = 0.3 I_{th}$) a typical emission spectrum is shown in Fig. 3(a). The full width at half-maximum (FWHW) of the luminescence line is 58 meV. This linewidth is $2.2kT$, i.e., larger than the spontaneous emission linewidths of $1.8kT$ in homogeneous semiconductors with a square-root-shaped density of states or of $0.7kT$ in two-dimensional systems with a step-function-like density of states. The broader linewidth is probably caused by geometric size fluctuations of the quantum wells.[8] The observed linewidth of spontaneous emission is comparable to linewidths in the $Al_xGa_{1-x}As$/GaAs and $Ga_xIn_{1-x}As/Al_yIn_{1-y}As$ quantum well systems.[9] The radiative recombination at 300 K involves most likely transitions from the lowest conduction subband to the lowest valence subband. The two-dimensional behavior of carriers in delta-doped GaAs, i.e., the population of subbands, was indeed confirmed by magnetotransport measurements.[10] Furthermore, we have observed 300-K spontaneous electroluminescence up to a wavelength of 1 μm depending on the design parameters of th STS. Such long wavelengths have not been observed in compensated highly doped bulk-type GaAs.

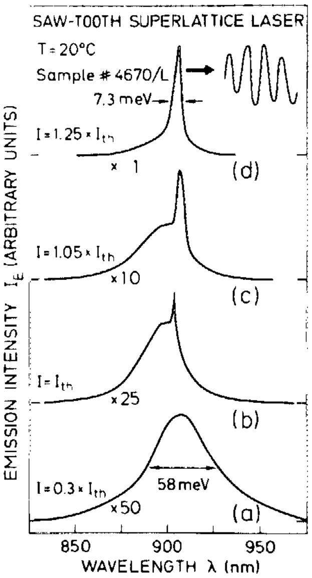

FIG. 3. Spontaneous and stimulated emission spectrum at room temperature of a broad-area GaAs sawtooth superlattice injection laser at various currents. The full widths at half-maxima of the spontaneous and stimulated emission are 58 meV ($\Delta\lambda = 38$ nm) and 7.3 meV ($\Delta\lambda = 4.8$ nm), respectively.

An increase of the injection current results in laser operation of the diode, as shown in Figs. 3(b)–3(d). The threshold current density is 2.2 kA/cm^2 ($I_{th} = 1.4$ A) for broad-area lasers, which represent as yet nonoptimized structures. The peak wavelength of the stimulated emission spectrum is 905 nm, longer than wavelengths obtained from conventional $GaAs/Al_xGa_{1-x}As$ double heterostructure lasers. The full width at half-maximum of the stimulated emission spectrum at a current of $I = 1.25 I_{th}$ is only 7.3 meV, which is much smaller than the thermal energy of $kT = 25.9$ meV at room temperature. The horizontal axis of the stimulated emission spectrum shown in Fig. 3(d) is enlarged in the inset to resolve the Fabry–Perot modes of the laser line.

In Fig. 4 the integrated optical intensity, measured by a Si photodiode at a temperature of 20 °C, is depicted as a function of the injection current. The integral intensity of the GaAs STS laser increases slowly for small current densities. For currents larger than the threshold current, however, the intensity increases steeply due to the short radiative lifetime of stimulated recombination of carriers. The stimulated emission of the new semiconductor superlattice laser at an

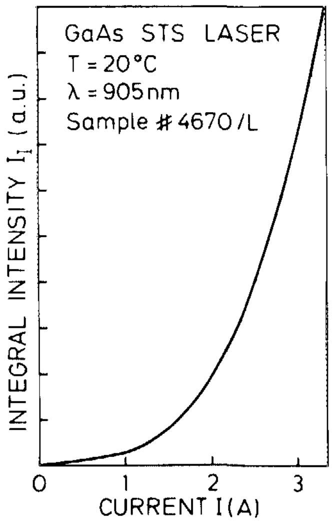

FIG. 4. Integrated light intensity of a broad-area sawtooth superlattice laser vs exciting current at room temperature for a $250 \times 250\,\mu m^2$ device.

energy significantly below the bulk GaAs band gap at room temperature indicates that free carriers in the active region do *not* screen the charge of ionized localized impurities, even during laser emission where population of conduction and valence subbands is highly degenerate. This manifests a high stability of the superlattice band gap, a favorable characteristic of the new sawtooth superlattice. Furthermore, this result indicates that the superlattice band-gap energy E_g^{SL} can be *preselected* by a proper choice of the material design parameters, but it *cannot* be *tuned* by the injection current.

In summary, we have presented a new type of superlattice injection laser grown by molecular beam epitaxy. The active region of the laser consists of alternating n-type and p-type Dirac-delta doped GaAs layers. Thus, a sawtooth-shaped conduction-band and valence-band edge is generated. The forward I-V characteristic of the sawtooth superlattice (STS) laser exhibits a threshold voltage of 1 V which indicates the superlattice character of the active region. The band-gap energy of the STS is smaller than that of the GaAs host material. The laser operation demonstrates the stability of the superlattice band gap even at high excitation currents. Broad-area lasers emit stimulated radiation at a wavelength of 905 nm, a range inaccessible by conventional GaAs lasers with an undoped active region. The threshold current density of the injection laser is 2.2 kA/cm^2 for non-optimized structures during pulsed excitation.

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