Tunable stimulated emission of radiation in GaAs doping superlattices

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Tunable stimualted emission of radiation is achieved in $Al_xGa_{1-x}As$/GaAs double heterostructures, in which the waveguiding GaAs region consists of a delta-doped doping superlattice. The low-temperature emission energy is 45 meV below the bulk band gap of GaAs for homogeneous optical excitation of the Fabry–Perot cavity. The emission energy is continuously tunable over 35 Å by inhomogeneous excitation of the cavity.

In this letter we report on stimulated emission of radiation from a delta-doped GaAs doping superlattice confined between $Al_xGa_{1-x}As$ barriers. Optical excitation of the double heterostructure results in stimulated emission of radiation at energies below the bulk band gap of GaAs. Continuously tunable emission of radiation is achieved for the first time by inhomogeneous excitation of the laser cavity.

Doping superlattices were proposed approximately two decades ago.[1–3] Such doping superlattices consist of a semiconductor which has alternating *n*-type and *p*-type doped regions along the growth axis. A periodic potential results from the positive and negative donor and acceptor charges, respectively. Doping superlattices exhibit unique properties which include (i) a superlattice energy gap smaller than the fundamental gap of the (bulk) host semiconductor, (ii) spatial separation of electron and hole wave functions, and (iii) a smaller oscillator strength of optical transitions as compared to bulk materials. Long-period doping superlattices have tunable characteristics[4] including the tunable gap energy which depends on optical excitation intensity and injection current. Semiconductor devices made from GaAs doping superlattices include the light-emitting diodes operating at room temperature at $\lambda = 980$ nm[5] and doping superlattice current-injection lasers[6] emitting coherent radiation at $\lambda = 905$ nm. Vojak *et al.*[7] also reported a photopumped doping superlattice laser which emitted light below the band gap of GaAs. However, both publications[6,7] revealed no evidence of tunability of the laser emission. Indeed a number of attempts to achieve tunable laser emission in doping superlattices remained unsuccessful.[4–7] Recently, significantly improved optical properties of doping superlattices have been obtained by employment of the δ-doping technique.[8] Quantum-confined optical interband transitions were observed in absorption spectroscopy[9] as well as in photoluminescence spectroscopy.[9] We attribute the improvement of the optical properties to reduction of dopant diffusion at low growth temperatures[8] and to the inherent advantages of the δ-doped structure.[10]

The epitaxial GaAs and $Al_xGa_{1-x}As$ layers used in this study were grown in a Vacuum Generator gas-source molecular beam epitaxy system on semi-insulating GaAs substrates. The epitaxial layer sequence consists of a 1.0-μm-thick $Al_{0.30}Ga_{0.70}As$ buffer layer, a 1700-Å-thick GaAs waveguiding active region, and a 0.6 μm $Al_{0.30}Ga_{0.70}As$ top layer. The active GaAs region consists of alternating *n*-type (Si) and *p*-type (Be) δ-doped spikes of concentration $N_D^{2D} = N_A^{2D} = 1 \times 10^{13}$ cm^{-2}. The doped regions are separated by 170 Å undoped GaAs. The doping superlattice consists of five periods. A schematic sketch of the layer sequence, the active region doping profile, and the corresponding band diagram are shown in Fig. 1. After epitaxial growth the layers are cleaved into bars of nominal 250 μm width and 1 cm length. A frequency-doubled Nd-doped *Q*-switched YAG laser ($\lambda = 532$ nm) is used for optical excitation. Light emission from the sample is detected with a Si detector using gated detection. The laser samples were cooled in a variable-temperature He cryostat.

The spontaneous and stimulated emission spectra are shown together with the light output versus excitation intensity curve in Fig. 2. In the spontaneous emission regime at low excitation intensity the peak wavelength moves to shorter wavelength with increasing excitation intensity. The shift of the spontaneous emission is well known in doping superlattices and is due to screening of dopant charges by free carriers[4] and band filling effects.[9] At higher excitation intensities stimulated emission occurs, which is accompanied by the characteristic kink in the light output curve of Fig. 2(a) and a narrowing of the emission spectrum below values of the thermal energy *kT*. However, the peak wavelength does not change in the stimulated emission regime as

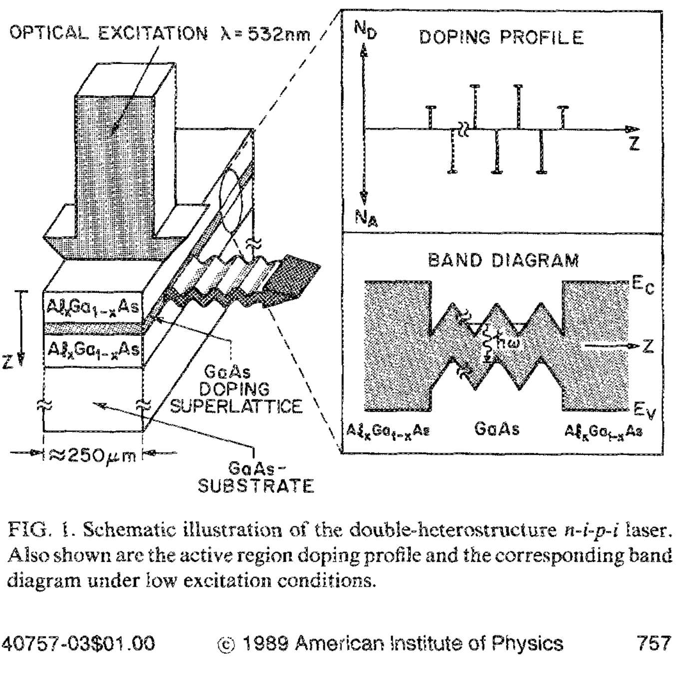

FIG. 1. Schematic illustration of the double-heterostructure *n-i-p-i* laser. Also shown are the active region doping profile and the corresponding band diagram under low excitation conditions.

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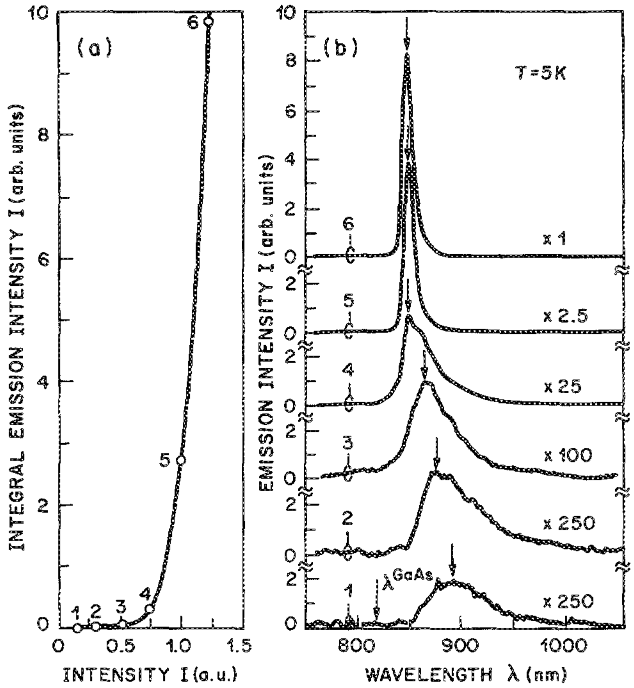

FIG. 2. (a) Light output vs excitation intensity of the doping superlattice laser. (b) Emission spectra for the spontaneous and stimulated regime. In the spontaneous emission regime, the photoluminescence peak shifts to smaller wavelengths. In the stimulated emission regime, the peak wavelength remains constant.

clearly revealed in Fig. 2(b). Such a constant emission energy is not unexpected, since upon reaching the laser threshold the Fermi level remains constant and additional carriers undergo stimulated recombination with a correspondingly very short lifetime. Thus, the emission energy remains constant with excitation energy in the stimulated emission regime.

The emission energy can be tuned continuously by inhomogeneous excitation of the Fabry–Perot cavity. Such inhomogeneous excitation is achieved by displacing the exciting beam from its centered position, as shown in the top part of Fig. 3. The inhomogeneous excitation results in a laser emission energy higher as compared to the symmetric excitation. Figure 3 reveals that the tuning range of the laser is approximately 35 Å. This tuning range does not represent a fundamental limit. The current tuning range is limited by the intensity distribution of the exciting source. We expect a wider tuning range for a more imhomogeneous excitation, which could be also achieved in a two- or three-section current-injection laser.

Simultaneously, as the peak of the stimulated emission shifts to shorter wavelength, the excitation intensity required to reach threshold increases, as illustrated in Fig. 3(b). However, it is important to visualize that upon displacement, the sample is excited only by a small part of the exciting beam as shown in the inset of Fig. 3. Thus, the increase of threshold intensity is overestimated and the true increase in threshold intensity is not as pronounced as suggested by Fig. 3(b).

A high-resolution spectrum of the doping superlattice laser is shown in Fig. 4 for the transverse electric (TE) and transverse magnetic (TM) mode. As expected in conventional $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs double-heterostructure lasers with the cleavage planes being a $\{110\}$ plane, the TE mode dominates the laser emission, while the TM mode is comparatively weak.

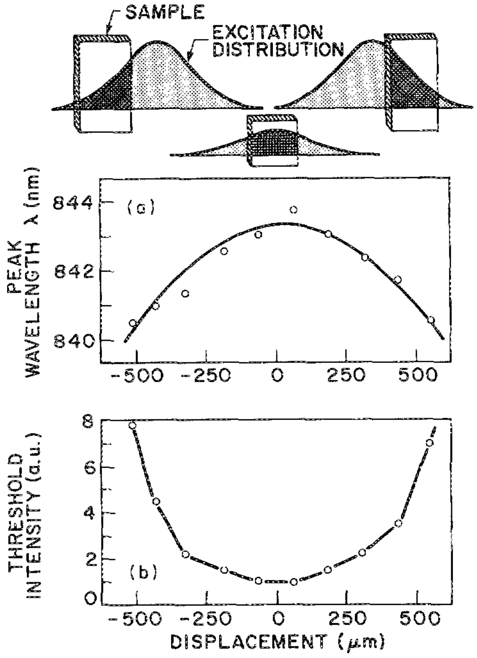

FIG. 3. (a) Peak wavelength of the laser spectrum and (b) excitation intensity of the doping superlattice laser vs the displacement of the exciting beam.

Under homogeneous excitation conditions the stimulated emission energy is below the band gap of GaAs. However, the emission energy is much higher than the spontaneous emission energy at low excitation intensities ($E \simeq 1.35$ eV). Thus, the superlattice modulation is reduced by photoexcited electrons and holes, which screen the ionized dopant

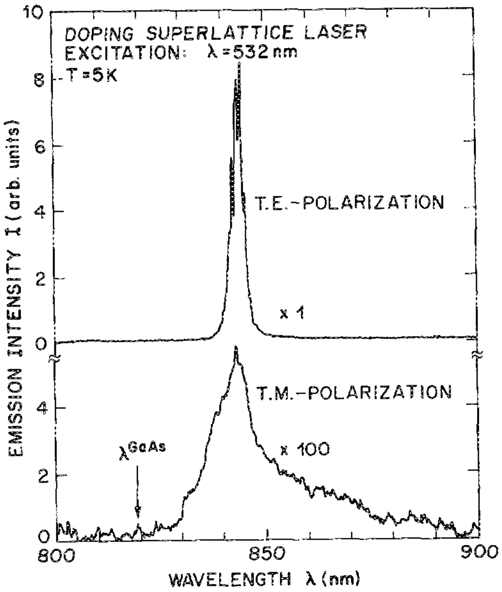

FIG. 4. Stimulated emission spectrum of the doping superlattice laser with transversal electric (TE) and transversal magnetic (TM) polarization. The TE polarization spectrum reveals a number of longitudinal modes.

charges of donors and acceptors, respectively. Even though the modulation is reduced, a residual band modulation is still maintained, as suggested by the low emission energy. Thus, stimulated emission is achieved, before the bands are completely flat, that is, for incomplete screening of dopant charges. Impurity-assisted transitions are unlikely for the δ-doped *n-i-p-i* structure used here, since the recombination occurs in the intrinsic layers between the doped regions (see Fig. 1). Furthermore, the relatively low temperatures used during crystal growth make diffusion and segregation of the dopants irrelevant.[8]

The physical mechanism leading to the tunability of the semiconductor laser can be understood on the basis of increased loss induced by inhomogeneous excitation. As a result of the inhomogeneous excitation, i.e., reduced excitation intensity in one part of the Fabry–Perot cavity, the optical loss is enhanced in this section. In order to obtain stimulated emission the other section must be subjected to higher excitation. As a result, the band modulation decreases and the superlattice energy gap increases in this section due to an enhanced density of carriers. Once the intentionally induced loss is overcome, stimulated emission occurs. However, the corresponding energy is increased as compared to the homogeneously excited cavity. Thus, tunability of the stimulated emission wavelength is achieved by a different excitation in the two sections of the laser. The principal limit of the tuning range is reached when flatband condition is achieved in one part of the laser. The corresponding tuning range is approximately 250 Å at low temperatures for the samples studied here.

At higher temperatures the tuning range of the laser samples is reduced. The stimulated emission peak can be tuned up to temperatures of 150 K. At room temperature stimulated emission is achieved in approximately 50% of our samples. The absence of room-temperature laser emission in some of our samples may be the result of the weaker oscillator strength in doping superlattices as compared to bulk material; it may also be a result of the low growth temperatures (500–550 °C), which are employed to keep diffusion of dopants minimal. The room-temperature emission energy cannot be changed upon inhomogeneous optical excitation. The absence of tunability is attributed to the relatively high excitation intensity necessary at 300 K. Such high excitation intensities tend to screen impurity charges and eliminate the superlattice potential.

In conclusion, tunable stimulated emission of radiation in doping superlattices is demonstrated for the first time at low temperatures. The doping superlattice consists of a δ-doped *n-i-p-i* structure with a sawtooth-shaped conduction and valence band embedded in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layers. Homogeneous optical excitation results in stimulated emission below the bulk bandgap of GaAs at constant energy independent of excitation intensity. Inhomogeneous optical excitation allows us to continuously tune the emission wavelength over approximately 35 Å at low temperature. The samples investigated in this study have a potential tuning range of 250 Å. Stimulated emission is obtained in the entire temperature range 5–300 K.

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