TASERs: Possible dc pumped terahertz lasers using interwell transitions in semiconductor heterostructures

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We have carried out a theoretical analysis of a possibility to generate coherent continuous-wave terahertz radiation using double-quantum-well heterostructures. The lasing should take place due to inversed population of the wells, created by electron flow through the structure under the effect of applied dc voltage. Estimates show that, e.g., 3 THz radiation with a relatively narrow line ($\Delta f/f \lesssim 10^{-5}$) and power of the order of 0.1 mW may be generated using structures with area as small as $\sim 100\ \mu\text{m}^2$, at temperatures up to ~ 30 K. For the experimental implementation of this opportunity, a special design is suggested to reduce absorption of terahertz radiation.

The terahertz frequency range (1–10 THz) still lacks convenient sources of coherent narrowband radiation, especially compact dc-powered generators which could be readily used in integrated circuits. Several suggestions of lasers which would use intersubband transitions in semiconductor heterostructures were put forward (see, e.g., Refs. 1–4 and references therein). The goal of this paper is to suggest one more opportunity which seems to have substantial advantages.

Consider a double-well structure with the band-edge diagram shown in Fig. 1(a). Quantization of electron motion in the z direction (perpendicular to the layers) in each well leads to formation of the subbands with the dispersion relation

$$\varepsilon_{L,R}(p_\perp) = \varepsilon_{L,R} + p_\perp^2/2m, \tag{1}$$

where $p_\perp$ is the momentum perpendicular to z. The effective electron mass m is the same in both wells, so that every electron which tunnels through the middle energy barrier M with conservation of $p_\perp$ changes energy by the same amount:

$$\varepsilon_L(p_\perp) - \varepsilon_R(p_\perp) = \Delta. \tag{2}$$

The interwell transitions can be either nonradiative, resulting from the combination of electron tunneling between the wells and electron scattering within each well, or radiative, resulting from absorption/emission of the energy difference Δ by an electromagnetic field of frequency $\omega_0 = \Delta/\hbar$. The population inversion, necessary for dominance of the photon emission over absorption, can be naturally sustained by dc current flow j through the "external" tunnel barriers L and R. In the simplest case when these barriers are sufficiently transparent, while the interwell tunneling rate is low, one well [the right one in Fig. 1(a)] is virtually empty, while the second (left) well is filled up to the transversal energy E, determined by the Fermi level in the external electrode. The energy E determines the maximum number of electrons per unit area $n_{\max} = \rho E$ participating in transport ($\rho = m/\pi\hbar^2$ is the two-dimensional density of states).

In our previous work,[5] we have considered spontaneous "Bloch" radiation due to these transitions, and also calculated the response of the system to a small external rf signal, including its specific rf admittance $y(\omega)$ (per unit area).[6] At frequencies near ω_0, the real part of the admittance may exhibit a negative peak of width $\sim\gamma$, where $\gamma = (\Gamma_L + \Gamma_R + \Gamma)/2$ is the total reciprocal phase relaxation time, Γ is the electron scattering rate, while $\Gamma_{L,R}$ are rates of tunneling through the external barriers. The negative peak of $\text{Re}\,y(\omega)$ is a manifestation of the radiation-stimulated interwell transitions, and indicates that the system is capable of lasing, if the heterostructure is complemented by a proper resonator.

Let us analyze this possibility, assuming that a resonator fixes sinusoidal ac voltage $A \cos \omega t$ across the heterostruc-

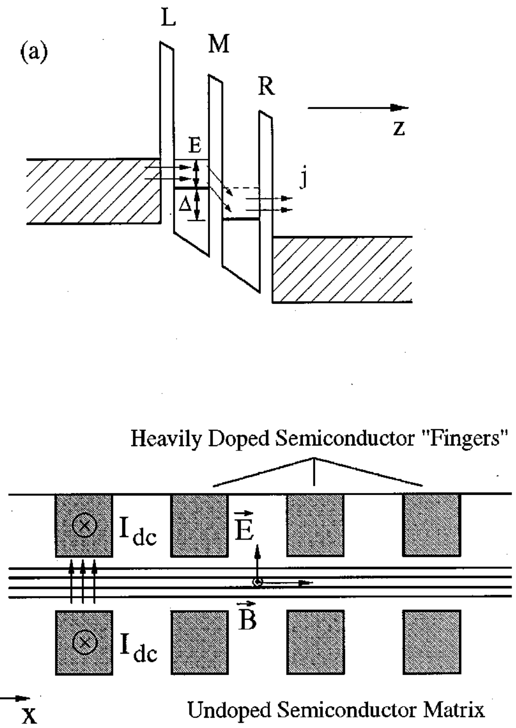

FIG. 1. TASER: (a) Energy band diagram of the active region and (b) possible structure. Inclined arrows in (a) show the radiative transitions of the electrons with transverse momenta $p_\perp$ within the range $0 < p_\perp^2/2m < E$. In (b), dashed areas show heavily doped GaAs.

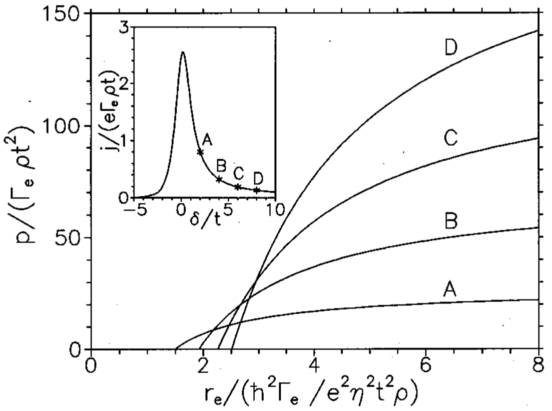

FIG. 2. Specific power of coherent radiation as a function of external impedance, for several values of dc voltage. These values are marked at the dc *I-V* curve (inset) of the same heterostructure in the absence of lasing. $\Gamma_L=\Gamma_R=\Gamma_e\gg\Gamma$. It is assumed that the dc voltage drops equally at the emitter barrier and interwell barrier. $E_F-(\varepsilon_L+\varepsilon_R)/2=5t$ at $\delta=0$; temperature is well below Δ.

ture. Substituting the expression $V=V+A\cos\omega t$ into equations of Ref. 5, it is straightforward to find the stationary solution satisfying the additional equation $A=-j_1r_e$, where j_1 is the in-phase quadrature amplitude of the first harmonic of the current density $j_e(t)$ through the heterostructure, while r_e is the specific ac resistance of the resonator as seen by the heterostructure. The amplitude A also determines the radiation power per unit area $p=A^2/2r_e$.[7]

Figure 2 shows the result of such a calculation. The lasing starts when $1/r_e$ (which is proportional to the radiation loss) becomes less than the threshold value

$$1/r_0=|\mathrm{Re}\ y(\omega)|=\eta e^2t\ \sin\varphi\ \cos\varphi\ n/2\hbar^2\gamma, \tag{3}$$

where $\varphi=\arctan[(\Delta-\delta)/t]$, t is the tunnel matrix element for the middle barrier, δ represents the levels shift at $t=0$ [at $t\neq0$, $\Delta=(\delta^2+t^2)^{1/2}$], and $\eta\simeq1/3$ is a geometrical factor,[5] while $n=\Sigma_p[n_1(p)-n_2(p)]$ is essentially the population inversion (per unit area). In the general case, n can be evaluated using equations of Ref. 5, but if the subbands are far enough from alignment, $\Delta\gg t[\gamma(\Gamma_L+\Gamma_R)/\Gamma_L\Gamma_R]^{1/2}$, the sum equals just $n_{\max}\equiv\rho E$. At $r_e/r_0\rightarrow\infty$, the power saturates at the level

$$p_{\max}\approx\frac{\Gamma_L\Gamma_R}{\Gamma_L+\Gamma_R}n_{\max}\Delta \tag{4}$$

(this equation is strict at $\varphi\approx t/2\delta\ll1$).

One more important parameter of a laser is its linewidth. In our case, the linewidth is due to, first, thermal and quantum fluctuations of the electromagnetic field in the resonator and, second, shot-type noise due to nonradiative electron transitions between the subbands. Our calculations (to be published elsewhere) show that, as in usual lasers (see, e.g., Ref. 8), well above the threshold (3) the linewidth is of the order of $\gamma/n_{\max}S$, where S is the device area.

Let us use these results to estimate possible parameters of the laser (probably, TASER would be a better abbreviation for a terahertz-band generator of stimulated radiation). Though the results of Ref. 5 were obtained using the assumptions $\gamma\ll t$, $\Delta\ll E_F$, they should be semiquantitatively valid even when these groups of parameters are close. Consider a GaAs/AlGaAs structure ($m=0.067m_0$, $\rho\simeq3\times10^{13}$ cm^{-2} eV^{-1}). For a realistic energy range $E\simeq6$ mV, $n_{\max}$ is close to 2×10^{11} cm^{-2}. Because E is well below the optical phonon energy, in low-defect structures and at relatively low temperatures (see below), the scattering rate Γ should be mostly determined by electron-electron interaction. Despite the substantial controversy in estimates of this rate in 2DEG structures,[9,10] recent direct experiments[11] seem to confirm earlier theoretical calculations.[12,13] According to these calculations, for the accepted values of E and n the rate does not exceed 10^{12} s^{-1} for temperatures at least below 30 K (and is not much higher at 77 K).

Now, for a moderate tunneling amplitude $t\simeq4$ meV (still well above $\hbar\gamma\simeq1$ meV) we still can use results of Ref. 5 to evaluate $|\mathrm{Re}\,y(\omega)|$. For example, for frequency 3 THz ($\Delta=12$ meV, so that $\sin\phi\simeq t/2\Delta\simeq1/6$, $\cos\phi\simeq1$), Eq. (3) yields the specific negative conductance $|\mathrm{Re}\ y(\omega)|\simeq2\times10^6\ \Omega^{-1}$ cm^{-2}. This figure is only slightly less than the specific capacitive admittance of the double-well structure $\omega c\simeq6\times10^6\ \Omega^{-1}$ cm^{-2}, where we have used $\varepsilon\simeq12$, and the total thickness $d\simeq30$ nm. Thus, the resonance resistance $r_e=Q/\omega c$ exceeds the lasing threshold r_0 (3) if the cold quality factor Q of the resonator is higher than quite a moderate value $\omega c/|\mathrm{Re}\ y(\omega)|\sim3$.

For the estimation of the generated power let us use the area $S=100\ \mu$m^2 and rates $\Gamma_L\simeq\Gamma_R\simeq5\times10^{11}$ s^{-1}; then according to Eq. (4), $P_{\max}\simeq0.1$ mW. Because of the small absolute number of involved electrons $N=nS\simeq2\times10^5$, the radiation linewidth is considerable ($\Delta\omega/\omega\gtrsim3\times10^{-6}$). Nevertheless, despite relatively low power and wide line, such "microlasers" may be quite useful for some applications, especially as local oscillators in imaging focal arrays.

The main problem in experimental realization of TASERs is the strong absorption of terahertz radiation in doped GaAs. Consider first a simple resonator formed by patterning a mesa in the double-well heterostructure sandwiched by heavily-doped semiconductor electrodes. Assuming the doping level $n_d\simeq10^{18}$ cm^{-3}, we may write the following Drude estimate for the effective dielectric constant

$$\varepsilon'(\omega)\simeq\varepsilon_\infty\left(1-\frac{\omega_p^2}{\omega^2(1-i/\omega\tau)}\right),\qquad \tau=m\mu/e, \tag{5}$$

where for our parameters the plasma frequency $\omega_p^2=n_de^2/\varepsilon_\infty\varepsilon_0m$ is close to 6×10^{13} sec^{-1}, $\varepsilon_\infty\simeq12$, so that $\mathrm{Re}\ \varepsilon'(\omega)\simeq-100$. (In our case, the contribution from the optical phonons[14] can be neglected.)

Wave propagation in a three-layer structure consisting of a layer with thickness d and dielectric constant $\varepsilon>0$, sandwiched between two electrodes with negative dielectric constant ε', can be considered in a standard way (see, e.g., Ref. 15). For our parameters ($d\approx30$ nm, $\varepsilon\approx12$, $\varepsilon'\approx-100$) the wavelength appears to be extremely small, $\lambda_{\mathrm{ef}}=2\pi/k\simeq\pi d|\varepsilon'|/\varepsilon\approx1\ \mu$m, while the depth of field penetration into the doped electrodes is practically equal to k^{-1}, and Q is close to $\omega\tau$ (for $\omega\tau\gg1$). For the corresponding mobility 4×10^3 cm^2/V s this estimate gives $Q\simeq3$, which is close to the lasing threshold. Even if the lasing occurs, however, the available power and the linewidth will be much worse than the estimates which were given above, because the radiation decay length $L=Q/k$ is very small ($\sim$0.5 μm).

Thus, a special design is necessary for reduction of absorption. One possible way is to provide dc current injection into the double-well structure using strips of heavily doped GaAs, perpendicular to the direction x of wave propagation [Fig. 1(b)], inside the insulator matrix. Such geometry reduces the absorption (and hence increases Q) sharply, because the electric field $\mathbf{E}$ is perpendicular to the conducting strips. In addition, the striped wire geometry restores the wavelength $\lambda_{\rm ef}$ to the usual value $\sim\lambda_0/\sqrt{\varepsilon}\sim 30$ μm, and hence increases L. The major problem with this geometry is the relatively small dc conductivity of strips. Assuming the strip thickness about 1 μm and the doping level of 10^{18} cm^{-3}, its sheet resistance can be estimated as 15 $\Omega/\square$. In order to provide the current density through double-well structure (in our estimate above, on the order of 10^4 A/cm^2) without a considerable gradient of voltage, the strip length should be not longer than several micrometers. It restricts one dimension of the active area, so that in order to implement the area $S=100$ μm^2 mentioned above, the length of the laser should be at least several tens μm.

Note that the lasing can be registered not only via direct observation of the emitted radiation, but also via the associated sharp increase of the dc current through the heterostructure. For a narrow-band resonator, the resulting current peak in their I-V curves shall be similar to those shown in Fig. 5 of Ref. 5 (see also earlier work[17]). dc charge accumulation effects can result in a finite slope of the peak. The left slope of the peak corresponds to a large positive dc differential conductance of the structure, even if dI/dV in the absence of lasing ($A=0$) is slightly negative (as it is for the example shown in the inset of Fig. 2). It means that the lasing prevents the parasitic relaxation oscillations.

To summarize, we have found that resonant interwell tunneling in double-quantum-well heterojunctions make them uniquely suitable for generation of stimulated coherent cw radiation in the terahertz frequency band. In contrast to alternative proposals based on intersubband transitions in one well, the structure exhibits simultaneously at least the following attractive features:

(i) Natural, dc-current-induced population inversion. (In fact, two active levels are located in different wells and are naturally coupled to different electron reservoirs.)

(ii) Large dipole momentum of interwell transitions (oscillator strength is of the order of unity). Though for intrawell transitions the oscillator strength may be equally high, in double-well structures the well width and the generated frequency are uncoupled parameters, making the structure more convenient for experimental implementation. It is also important that the possibility to adjust the relative subband positions by the bias voltage relaxes tolerances for the design and fabrication errors.

(iii) Convenient option of electronic tuning of the radiation frequency $\omega_0=\Delta/\hbar$ by the applied dc electric field within the range $\sim\omega_0/Q$ which may be as broad as $\sim 0.3\omega_0$.

Note that according to our formulas, the lasing threshold can be exceeded even in structures with $Q<1$ (say, by increasing E to $\sim$20 meV, while retaining all other parameters of our example set). In this case, our theory may not be applicable, because the ac voltage across the heterostructure may become a highly non-sinusoidal function of time. Thus, we cannot exclude the possibility of appearance of either relaxation-oscillation, or chaotic, or some other unusual dynamic phenomena in this mode. Further theoretical and experimental studies of such ‘‘relaxation lasers’’ are certainly needed.

Note added. After submission of the manuscript we have learned about the first successful demonstration of a laser based on interwell transitions in a periodic heterostructure with three quantum wells per period.[16] This important experimental achievement supports the basic idea of present paper. Nevertheless, we still believe that our double-well structure is simpler than the three-well structure used in Ref. 16, and that the special absorption-suppression design discussed above will be critical for lasing at terahertz frequencies (in the experiments[16] the radiation frequency was much higher).

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[6] In fact, calculations in Ref. 5 were carried out for a slightly different case when the Fermi energy in the collector electrode is higher than the 1D quantization levels. However, the final results of that work are applicable to the present case, with the replacement $(eV-\Delta)\rightarrow E$.

[7] The ‘‘impedance-admittance’’ language accepted in this work is equivalent to the usual language of loss-gain balance. While the latter language is more traditional in the literature on lasers, we believe that our formulation is more natural for any system where the thickness d of the active region (but not necessarily the planar size of the device) is much smaller than the radiation wavelength.

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