In conclusion, it was demonstrated that the intrinisic modulation response of injection lasers can be modified by varying mirror reflectivities, with a resulting suppression of the relaxation oscillation resonance and a reduction of nonlinear distortions at multi-GHz frequencies. In addition, the flatness of the response extends the useful bandwidth of these lasers up to the point of the final high-frequency cutoff. Although experiments were performed on only one type of laser, it is expected that these results, which are manifested by basic superluminescent effects, apply to other laser structures as well.

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Internal photoemission from quantum well heterojunction superlattices by phononless free-carrier absorption

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The possibility of phononless free-carrier absorption in quantum well heterojunction superlattices was investigated. Order of magnitude calculation showed that the absorption coefficient was significantly enhanced over the phonon-assisted process. Important aspects of the enhancement in the design of infrared photodetectors are discussed.

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Recently, a novel infrared photodetector using free-carrier absorption to excite electrons in a quantum well GaAs/GaAlAs heterojunction superlattice structure has been demonstrated.[1,2] In GaAs, the normal phonon-assisted free-electron absorption in a quantum well was found to be enhanced by a factor of 3–5 over its bulk value.[1] Despite this enhancement, the coefficient of free-carrier absorption, α, is still quite small. In view of this, the first detector working on this principle was designed to be an edge detector to provide a long interaction length.[2] Further investigation, however, revealed that phononless free-carrier absorption in a quantum well structure was possible, with further enhancement in the absorption coefficient.

In this letter we present an approximate calculation for α_f^{pl} due to phononless free-carrier absorption in a quantum well. Estimated values for α_f^{pl} were over an order of magnitude larger than the phonon-assisted case, but much smaller than the direct inter-sub-band absorption.[3] This is expected since the transition matrix element is now first order as compared to the second order phonon-assisted process, but the restriction on electron wave vector in the direction perpendicular to the superlattice plane renders it much smaller than the inter-sub-band absorption.

To demonstrate the effect of phononless free-electron absorption, an order of magnitude calculation for the absorption coefficient α_f^{pl} in a single quantum well was performed. If the actual superlattice structure is such that the wells are effectively decoupled (which is desirable to minimize the dark current in a detector), then the present result will also be a reasonable estimate for α_f^{pl} in such constructions.

Approximating the electron wave functions by

$$\psi_i = \left(\frac{2}{LA}\right)^{1/2} u_i(\boldsymbol{\rho}) e^{i\mathbf{k}\cdot\boldsymbol{\rho}} \sin\frac{\pi x}{L}, \tag{1}$$

$$\psi_f = \frac{1}{\sqrt{V}} u_f(\boldsymbol{\rho}) e^{i\mathbf{k}'\cdot\boldsymbol{\rho}} e^{ik_x x}, \tag{2}$$

where L is the width of well, $LA = V$ is the volume of the well $\boldsymbol{\rho}$ is the radius vector in the plane of the heterojunction (y-z plane), $\mathbf{k}$ the electron wave vector, u the periodic part of the Bloch function, and the subscripts i,f denote the initial and final states respectively. The interaction Hamiltonian is then given by

$$H_{fi} = -\frac{ie\hbar A_0\sqrt{2}}{2m_0 V}\int u_f^*(\boldsymbol{\rho}) e^{-i\mathbf{k}'\cdot\boldsymbol{\rho}} e^{-ik_x x} (\hat{e}_0\cdot\nabla) u_i(\boldsymbol{\rho}) \times e^{i\mathbf{k}\cdot\boldsymbol{\rho}} \sin\frac{\pi x}{L}\, d\boldsymbol{\rho}\, dx, \tag{3}$$

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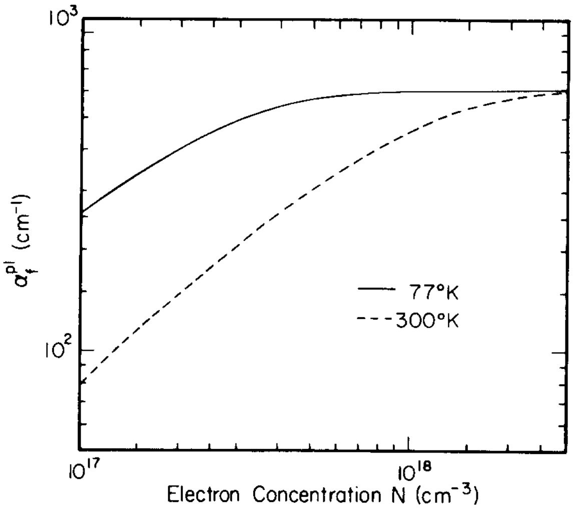

FIG. 1. Calculated phononless free-electron absorption coefficient as a function of electron concentration at 77 and 300 K.

where A_0 is the vector potential of the incident radiation field, m_0 the mass of free electron, and $\hat{e}_0$ the unit polarization vector of the electromagnetic field.

Invoking the periodicity of the crystal in the y-z plane, (3) can be simplified to

$$H_{fi} = \frac{eA_0\sqrt{2L}}{2m_0L} P_{fi} \int_0 \sin\frac{\pi x}{L} e^{-ik_x x}\, dx, \tag{4}$$

with the familiar condition for conservation of crystal momentum $\mathbf{k}' = \mathbf{k}$. The momentum matrix element P_{fi} in (4) is given by

$$P_{fi} = -\frac{i\hbar}{A'}\int_{\mathrm{uc}} (\hat{e}_0\cdot\hat{\rho})u_f^*(\boldsymbol{\rho})\frac{\partial}{\partial\rho}u_i(\boldsymbol{\rho})d\boldsymbol{\rho}, \tag{5}$$

where A' is now the area of the "unit cell" in the y-z plane, uc denotes unit cell, and the integration extends over one unit cell only in the y-z plane.

It follows immediately from (4) and (5) that the incident field would couple strongly only when the radiation is polarized in the y-z plane. Also, it is apparent from (4) that H_{fi} is finite unless k_x lies in the neighborhood of $m\pi/L$ with m an odd integer. Therefore, the structure can be designed to yield a finite H_{fi}, and thus results in phononless free-carrier absorption. Maximum coupling occurs near the vicinity of $m\pi/L$ when m is an even integer. It is the "phase" and energy matching restrictions that render α_f^{pl} much smaller than the "inter-sub-band" absorption. For GaAs/$\mathrm{Ga_{0.7}Al_{0.3}As}$ system designed to detect IR radiation around 4 μm,[1,2] with $L \approx 100$ μm, energy conservation dictates that m is around 2.5. The absorption coefficient is then given approximately by

$$\alpha_f^{pl} \approx \frac{0.048}{\epsilon_0\hbar c n_r}\frac{2}{m_0\hbar\omega}|P_{fi}|^2\left(\frac{m_c}{m_0}\right)\frac{1}{L}[1 - e^{-N\pi h^2L/m_ckT}], \tag{6}$$

where ϵ_0 is the permittivity of free space, n_r the refractive index (≈ 3), and N the electron concentration. To provide an order of magnitude estimate for α_f^{pl}, the momentum matrix element was assumed to be the form given in Ref. 4. The calculated α_f^{pl}, for the phononless absorption process as a function of N at 77 and 300 K is shown in Fig. 1. Compared to the phonon-assisted process,[1] it can be seen that the coefficient is more than an order of magnitude larger at the same electron concentration N.

This enhanced phononless free-carrier absorption has some significant implications. A necessary requirement according to (5) is that the radiation field be polarized in the plane of the heterojunction for strong coupling. A more important consequence is that excited electrons will continue to travel in the x direction, and when an external field is applied, a significant fraction of the excited electrons will be pulled out of the well region (see Fig. 1 of Ref. 2), thereby increasing the sensitivity and efficiency of the detector. The importance of this would be realized when compared to the phonon-assisted case, where the phonon absorption/emission process also randomized the electron momentum. In addition, the increased efficiency and absorption indicate that a surface detector is quite feasible, with the possibility of fabricating a detector array.

In summary, the phononless free-carrier absorption investigated here showed that the absorption was enhanced more than an order of magnitude over the phonon-assisted process. Significance of this enhanced absorption in the design of infrared photodetector was discussed.

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