Dynamic differential conductivity resonance at the cyclotron frequency in $Ga_{1-x}Al_xAs$ with ballistic intervalley electron transfer

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It is shown theoretically that in materials such as $Ga_{1-x}Al_xAs$ a resonance appears in the frequency dependence of the dynamic differential conductivity at the cyclotron frequency. The resonance frequency lies in the submillimeter range. The conditions for the appearance of such a resonance are determined and discussed. Such systems can be used for submillimeter-range, cyclotron-resonance masers.

1. According to Ref. 1 , under the conditions of ballistic (dynamic) heating of electrons with intervalley transfers (IVTs) in strong electric fields E in materials of the type $Ga_{1-x}Al_xAs$, two types of electrons (A and B) with different acceleration times (τ_E^A and τ_E^B, respectively) in an electric field up to the energy of intervalley transfer appear in the lower (Γ) valley. These electrons make different contributions to the differential conductivity (DC). The frequency dependence of the differential conductivity $\sigma(\omega)$ is determined mainly by the ratio of τ_E^A and τ_E^B:

$$\tau_E^A=\frac{eE}{P_0+P_1}, \quad \tau_E^B=\frac{eE}{P_0+P_1}, \quad P_{0,1}=\sqrt{2m_\Gamma^*(\Delta\epsilon\pm\hbar\omega^*)}, \tag{1}$$

where m_Γ^* is the effective mass of an electron in a Γ valley, e is the electron charge, $\hbar\omega^*$ is the energy of an intervalley phonon, and $\Delta\epsilon$ is the energy gap between the bottom (central) valley and the top valleys. In materials such as $Ga_{1-x}Al_xAs$ the values of this ratio can be easily controlled by varying x.

In Ref. 2 it was pointed out that a favorable situation for achieving submillimeter dynamic negative differential conductivity (NDC) can appear in a transverse magnetic field. Detailed investigations searching for NDC in a transverse magnetic field under conditions of dynamic intervalley transfer in systems such as $Ga_{1-x}Al_xAs$, where the range of electron motion in phase space can be varied within the limits of several $\hbar\omega^*$, have not yet been performed.

2. We investigated the differential conductivity in a strong electric and nonquantizing transverse magnetic fields at low temperatures ($k_0T\ll\hbar\omega^*$). The linearized Boltzmann equation for the small correction $f_\sim$, which appears in a low-amplitude alternating field $\mathbf{E}_\sim=\mathbf{E}_\sim^0 e^{i\omega t}$, to the distribution function was solved. The Monte Carlo method was used to construct the function $\sigma(\omega)$. The configurations of the fields are shown in Fig. 1a.

If the energy ϵ^X of the heated electrons in the X valleys is low because of their large effective mass ($\epsilon^X \ll \hbar\omega^*$), then after the $X \rightarrow \Gamma$ transitions the electrons are concentrated in a band near the isoenergy surface $\epsilon_1 = \Delta\epsilon - \hbar\omega^*$. The electrons crossing the surface $\epsilon_0 = \Delta\epsilon + \hbar\omega^*$ are transferred with characteristic time τ_0 into the X valleys, from which they again return with characteristic τ_1 into the Γ valleys, where a new acceleration cycle starts. If $\Delta\epsilon = 1 - 3\hbar\omega^*$ (this corresponds to solid solution compositions $0.34 < x < 0.39$), then the radius of the surface $\epsilon_1 = \text{const}$ is small, the electrons from different groups have similar transit times ($\tau_E^A \approx \tau_E^B$), and during the heating process their trajectories form a narrow bundle in momentum space. Under the conditions of dynamic heating this clustering remains along the cyclotron trajectories. The centers of these trajectories lie on the segment $(P_x, P_c, 0)$, $-P_1 < P_x < P_1$ ($P_c = cm_\Gamma^* E/H$, where c is the speed of light). The radii of these trajectories increase with increasing distance from the ZY plane, since the radii of the surface $\epsilon_1 =$ const and $\epsilon_0 =$ const in this plane change (decrease). These radii are $P_1' = \sqrt{P_1^2 - P_x^2}$ and $P_0' = \sqrt{P_0^2 - P_x^2}$, respectively; P_0' and P_1' have maximum values at $P_x = 0$ ($P_1' = P_1$, $P_0' = P_0$) and minimum values at $P_x = \pm P_1$ ($P_1' = 0$, $P_0' = \sqrt{P_0^2 - P_1^2}$). Hence it follows that the curvature of the cyclotron trajectories increases as P_x decreases. In the case

$$P_c \geq (P_0 + P_1)/2 = P_c^* \tag{2}$$

all trajectories are open (they intersect the surface $\epsilon_0 =$ const). The inequality (2) imposes a condition on the strengths of the electric and magnetic fields:

$$H/E \leq 2cm_\Gamma^*/(P_0 + P_1) = cm_\Gamma^*/P_c^* . \tag{3}$$

When the condition (3) is satisfied, no electron is yet confined in the magnetic "trap."

3. Under the conditions of bunching of the accelerated electrons, when the smearing of the band of cyclotron trajectories is small, magnetic fields satisfying the condition (3) are sufficient for a resonance to appear at the cyclotron frequency $\omega = \omega_c$($\omega_c = eH/m_\Gamma^* c$). It should be noted that the negative conductivity at zero frequency (static NDC which characterizes materials such as GaAs in the absence of a magnetic field) decreases in magnitude as the magnetic field increases.[3]

It turns out that for fields in which all trajectories are open, the sharpest resonance occurs at $\omega_c = \omega_c^*$, where

$$\omega_c^* = eH^*/m_\Gamma^* c = eE/P^* = 2eE/(P_0 + P_1). \tag{4}$$

From the conditions (3) and (4) we find the optimum relation between the electric and magnetic fields (between E^* and H^*):

$$H^*/E^* = 2cm_\Gamma^*/(P_0 + P_1). \tag{5}$$

It was determined that the electric fields E^* are sufficient for dynamic heating of electrons in a Γ valley for all gap widths $\Delta\epsilon$, such that NDC at the cyclotron frequency is possible. The quantities determined by the band structure of the material [including the quantities appearing in the condition (5)] depend on the composition of the solid solution.[4] The change in the parameter $\Delta\epsilon$ includes all details of the change in the band parameters.

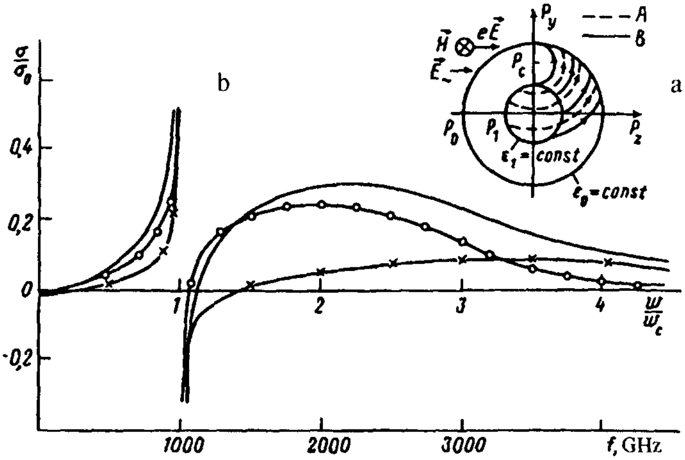

FIG. 1. a—Distribution of the electrons in the momentum space of the Γ valley (in the plane $P_x=0$) of a semiconductor of the type $Ga_{1-x}Al_xAs$ for the case of dynamic heating in crossed fields $\mathbf{E}\perp\mathbf{H}$. The diagram corresponds to fields $E=E^*$, $H=H^*$ [see Eq. (5)]. The arrows A and B indicate free motion of A and B electrons, $P_c=cm_\Gamma^*E/H$. b—Differential conductivity in the Γ valley; $\Delta\epsilon=1.7\hbar\omega^*$ ($Ga_{0.63}Al_{0.37}As$), $E=15$ kV/cm, $H=36$ kOe, $\omega_c=6.444\times10^{12}$ Hz; dots — differential conductivity of the A electrons; crosses—differential conductivity of the B electrons; curves with no points—total differential conductivity ($\sigma=\sigma^A+\sigma^B$); $\sigma_0=e^2N_X/m_\Gamma^*\nu_B^2\tau_1$ (N_X is the electron concentration in the X valleys, $\nu_E=lE/E_0$—transit frequency in a Γ valley).

The function $\sigma(\omega)$ shown in Fig. 1 corresponds to the case $E=E^*$, $H=H^*$. The results of the investigation show that as H decreases, the resonance peak decreases and vanishes when the magnetic field is no longer sufficient for resonance motion. Such a resonance is observed for gaps $\Delta\epsilon=1-8\hbar\omega^*$ ($0.2<x<0.39$). As $\Delta\epsilon$ increases further, the resonance is disrupted, because there are no distinct heating times in the system (due to the large scatter in their values) and the magnetic fields (3) are too weak for a pronounced resonance frequency to appear. For such values of $\Delta\epsilon$, the magnetic field must be increased until closed trajectories appear in the system.

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