3.7 to 5.5% and goes through a maximum of 6.6% when N_D increases from 4×10^{16} to 1.2×10^{18} cm^{-3}.

In summary, we have observed a first-order Stark effect in phosphorus-doped silicon from extrinsic photoconductivity when the driving electric field is changed. We relate this effect to a change of the overlap between the wave functions of electrons bound to neighbor-impurity centers.

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Parametric Excitation of Density Waves in Drifting Electron-Hole Plasmas*

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The effect of the electronic drift velocity on the conditions for parametric excitation in electron-hole plasmas is investigated in the two-mode approximation using a Vlasov-equations approach. The results show that when the electronic drift velocity approaches the phase velocity of the lower frequency mode of the plasma, a considerable lowering of the threshold for the onset of parametric excitation occurs, thus resulting in more favorable conditions for experimental observation of the process. The dependence of the threshold on other relevant physical parameters involved, such as the electron-to-hole mass and temperature ratios, is also investigated.

The interaction of high-intensity electromagnetic radiation with gaseous or solid-state plasmas may give rise to parametric effects of instability of plasma modes. In the last few years, considerable attention has been paid to these effects, both theoretically[1] and experimentally.[2]

Here we study in some detail how a constant drift velocity of one type of carrier against the other affects the threshold for parametric excitation in semiconducting electron-hole plasmas, with externally fixed ratios of concentrations n, masses m, and temperatures T, when interacting with high-intensity electromagnetic radiation. The information gained in studying parametric excitations in drifting electron-hole plasmas is expected to be useful for other kinds of two-component plasmas.

The drift velocity may become of crucial importance when the condition for the onset of the well-known linear instability is approached, as first pointed out by Lee and Su[3] (for instance, when the drift velocity of the electrons equals or exceeds the phase velocity of the lower frequency mode of an electron-ion plasma, which is the case Lee and Su considered). Owing to the large density fluctuation so induced in the system, an enhancement of the coupling of the external electromagnetic field with the modes of the plasma may be expected, and

as a consequence, a lowering of the threshold for the onset of parametric amplification may result. Since in a solid-state plasma we cannot use radiation of too high an intensity, such a lowering may considerably contribute to make parametric amplification more easily observable.

Let us suppose that the electron-hole plasma supports essentially two linear modes, a high-frequency "plasmon" mode and a low-frequency "acoustic" mode, with frequencies ω_p and ω_a, and dampings γ_p [4] and γ_a [5] calculated from a general dielectric function [6] under the condition that the phase velocities of the waves are far from hole and electron excitation frequencies kv_+ and kv_-, v_+ and v_- being the thermal velocities of the two types of carriers (the plus sign will stand for holes, the minus sign for electrons).

The frequency ω_0 of the external electromagnetic field

$$\vec{E}(\vec{r}, t) = \vec{E}_0 \sin(\vec{k}_0 \cdot \vec{r} - \omega_0 t) ,$$

$$\vec{B}(\vec{r}, t) = c(\vec{k}_0/\omega_0) \times \vec{E}(\vec{r}, t)$$

is chosen to be $\omega_0 = \omega_p + \omega_a$, which is the most favorable condition for parametric excitation to occur. The carrier concentrations n_+ and n_- are not assumed to be too high, so that a classical approach may be used.

Following a procedure rather similar to that used by DuBois and Goldman [1] for an electron-ion plasma, we start from the Vlasov equations

$$\frac{\partial f^{\pm}}{\partial t} + \vec{v} \cdot \frac{\partial f^{\pm}}{\partial \vec{r}} = -\vec{a}(\vec{v}, \vec{r}, t) \cdot \frac{\partial f^{\pm}}{\partial \vec{v}} \tag{1}$$

and

$$\vec{a}(\vec{v}, \vec{r}, t) = \frac{\pm e}{m_{\pm}} \left(-\vec{\nabla} U(\vec{r}, t) + \vec{E}(\vec{r}, t) + \frac{1}{c} \vec{v} \times \vec{B}(\vec{r}, t) \right) , \tag{2}$$

where $\vec{a}(\vec{v}, \vec{r}, t)$ is the acceleration of an electron (or hole) as a result of the self-consistent longitudinal field $\vec{\nabla} U$ and the Lorentz force of the total field $(\vec{E}, \vec{B})$; then we calculate the total nonlinear dielectric function, with the additional assumption (with respect to DuBois and Goldman) that the electronic equilibrium distribution function is a shifted Maxwellian, which takes into account that the electrons are drifting with a uniform velocity v_D against the holes assumed to be at rest.

Moreover, in deriving our basic nonlinear dielectric function we do not neglect the nonlinear contribution from the holes (which turns out to be m_-/m_+ times the corresponding electronic contribution) to the total polarization charge density, since in our case the ratio m_-/m_+ may not be too small. The presence of an electronic drift velocity appears, however, not to change significantly the nonlinear contribution to the total dielectric function.

Then by solving the equation for the total polarization charge density and the Poisson equation for U self-consistently, and truncating the resulting chain of equations in the usual manner, [7] we obtain the basic nonlinear dielectric function

$$\epsilon^{\mathrm{NL}}(\vec{k}, \omega) = \epsilon_D^{\mathrm{L}}(\vec{k}, \omega) - \frac{[\chi_-^{\mathrm{NL}}(\vec{k}, \omega; -\vec{k}, \omega_0 - \omega) + \chi_+^{\mathrm{NL}}(\vec{k}, \omega; -\vec{k}, \omega_0 - \omega)]^2}{k^4 \epsilon_D^{\mathrm{L}}(\vec{k}, \omega_0 - \omega)} , \tag{3}$$

where $\epsilon_D^{\mathrm{L}}(\vec{k}, \omega) = 1 + \chi_{-D}^{\mathrm{L}} + \chi_+^{\mathrm{L}}$ is the total linear dielectric function,

$$\chi_{-D}^{\mathrm{L}}, \chi_+^{\mathrm{L}}, \chi_-^{\mathrm{NL}} = \tfrac{1}{2} k^2 \vec{k} \cdot \vec{d} \quad \text{and} \quad \chi_+^{\mathrm{NL}} = -\tfrac{1}{4}(\omega_+^2/\omega_a^2) k^2 \vec{k} \cdot \vec{d}'$$

are, respectively, the electronic "drifted" and hole linear susceptibilities and the electronic and hole nonlinear susceptibilities, and

$$\vec{d} = -\frac{|e|}{m_- \omega_0^2} \vec{E}_0, \quad \vec{d}' = -\frac{m_-}{m_+} \vec{d} , \quad \omega_+^2 = \frac{4\pi n_+ e^2}{m_+} .$$

This result is obtained by assuming $k_0 \ll k < k_{\pm}$ (so that magnetic effects may be disregarded) and by using symmetry properties of nonlinear susceptibilities [1]; $k_{\pm}^2 = 4\pi n_{\pm} e^2 / k_B T_{\pm}$ are the hole and electron Debye screening wave vectors.

The threshold for parametric instability is found by setting $\mathrm{Im}\epsilon^{\mathrm{NL}}(\vec{k}, \omega) = 0$, which gives

$$E_0^2 = \frac{16\omega_0^4}{\cos^2\varphi e^2} \gamma_p \gamma_a \frac{[1 + (\Delta\omega)^2/(\gamma_p + \gamma_a)^2] k^2}{[k^2/m_- + \frac{1}{2}(k^2 + k_-^2)/m_+]^2 \omega_a \omega_p} , \tag{4}$$

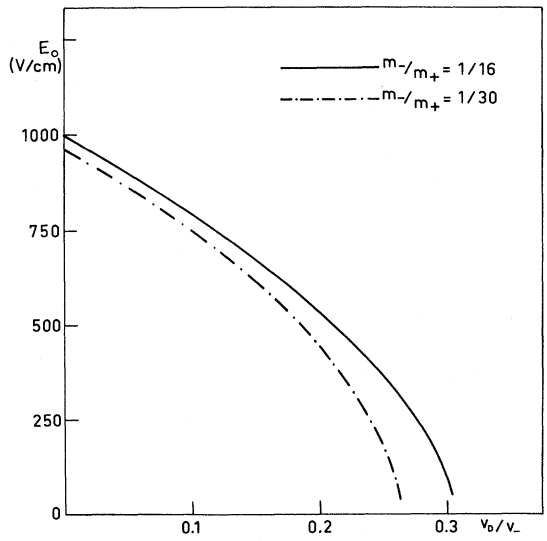

FIG. 1. Dependence of the threshold value of the field strength E_0 for the onset of parametric instability on the electronic drift velocity for $k = 0.32 k_-$, $T_- = 9T_+$, $n_+ = 2n_-$, and varying values of m_-/m_+. E_0 is given in V/cm and v_D in v_- units ($\cos\varphi = 1$).

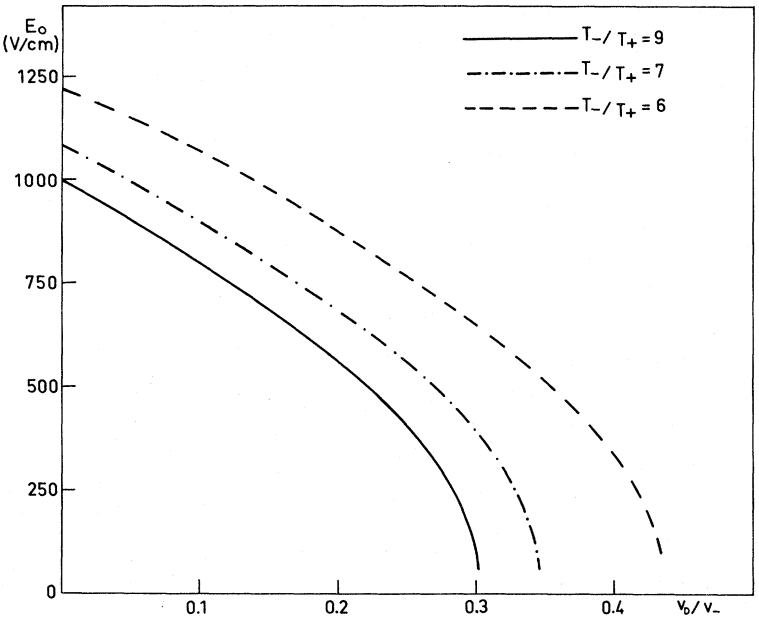

FIG. 2. Dependence of the threshold value of the field strength E_0 on the electronic drift velocity for $k = 0.32k_-$, $n_+ = 2n_-$, $m_-/m_+ = \frac{1}{16}$, and varying values of T_-/T_+. E_0 is given in V/cm and v_D in v_- units ($\cos\varphi = 1$).

where

$$\gamma_a = \left(\frac{\pi}{2}\right)^{1/2} \frac{\omega_a}{1+\beta^2}\left[\left(\frac{T_- n_+}{T_+ n_-}\right)^{3/2} \frac{1}{(1+\beta^2)^{1/2}} \times \exp\left(-\frac{T_- n_+}{2T_+ n_-(1+\beta^2)}\right) + \frac{1}{(1+\beta^2)^{1/2}} \times \left(\frac{m_- n_+}{m_+ n_-}\right)^{1/2} - \frac{v_D}{v_-}\right], \quad \beta = k/k_-$$

and ω_a, ω_p, and γ_p are well-known expressions,[6] $\Delta\omega = \omega_0 - \omega_p - \omega_a$ is the frequency mismatch, and $\cos\varphi$ comes from the term $\vec{k}\cdot\vec{E}_0$. Expression (4), except for the appearance of drift term in γ_a and the nonlinear contribution for the holes, is essentially the same as those derived by other authors for similar situations.[1] The threshold exhibits an explicit dependence on the mismatch condition, with a minimum for $\Delta\omega = 0$ as expected. The equation for the threshold has been solved numerically as a function of the electronic drift velocity v_D for different values of the relevant parameters, and the results are presented in Figs. 1 and 2.

The threshold is found to be lowered by a factor of about 10 when increasing the drift velocity v_D moderately and to depend more strongly on the temperature ratio than on mass ratio. Numerical computations, unreported here, also show a considerable lowering of the threshold with the electronic temperature T_-. However, an approximate analytical expression for the dependence of $\vec{E}_0$ on T_- may easily be obtained from Eq. (4) by putting

$$\Delta\omega = 0, \qquad k^2 \ll k_-^2 = \frac{4\pi n_- e^2}{k_B T_-},$$

$$\cos\varphi = 1, \qquad \omega_0^2 \approx \omega_p^2 \approx \frac{4\pi n_- e^2}{m_-}.$$

Formally, both γ_p and γ_a might be made arbitrarily small by taking high $k_\pm/k$ ratios in the case of γ_p and by making v_D equal to the phase velocity of the acoustic mode. However, since our approximate treatment does not cover these extremal situations, we refrain from considering Eq. (4) under these critical conditions. Finally, we note that our estimate of E_0 for $v_D = 0$ is greater than Tzoar's[8]; however, there is no "discrepancy" because of the different situations considered (Tzoar considered a quantum electron-hole plasma), and because in Ref. 8 no numerical value of the relevant parameters involved is reported.

Taking $n_- = 0.6\times10^{15}$, $n_+ = 0.3\times10^{16}$, $m_- = 0.03m_0$, $m_+ = 0.5m_0$, $T_- = 160\,^\circ$K, and $T_+ = 40\,^\circ$K (values which are expected to be realistic in InSb), and with $v_D/v_- = 0.5$, we obtain $E_0 = 130$ V/cm.

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[4]In the course of the calculations we have considered only the Landau damping and neglected the collisional damping (see DuBois and Goldman, Ref. 1). Since the Landau damping $\gamma_p \to 0$ when $k \to 0$, this must be considered a lower boundary on the permitted values of k.

[5]γ_a will be proportional to a term containing the factor $(\omega - \vec{k}\cdot\vec{v}_D)$, v_D being the electronic drift velocity, a well-known result (see also Ref. 6).

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Temperature Modulation of the Optical Constants of Layer Compounds GaSe and GaS

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We report the thermoreflectance spectra of the layer compounds GaSe and GaS at liquid-nitrogen temperature in the energy interval 2–6 eV. The spectra were subjected to a Kramers-Kronig analysis, and the changes in the real and imaginary parts of the dielectric constant, induced by the temperature change of the samples, were obtained. The optical constants of the two materials were computed by processing the known reflectivity spectra. A phenomenological interpretation of the observed experimental results is presented. It is shown that under certain conditions it is necessary to invoke the presence of excitons at saddle-point singularities in order to achieve reasonable agreement between theory and experiment.

I. INTRODUCTION

Temperature modulation is observed as a change in the reflectance of a semiconductor induced by a periodic variation of the reflecting-surface temperature.[1,2] Since the reflectance modulation gives rise to a pronounced structure of peaks at approximately the photon energies of interband transitions, this effect adds to the information on band-structure analysis extracted from optical studies on semiconductors. Moreover, the differential nature of the effect considerably enhances the structures in comparison with ordinary reflectance studies, providing much higher resolution and sensitivity.

Thermoreflectance measurements on semiconductors and semimetals have been made by Batz on Ge,[1,3] by Lange and Henrion on CdS and Se,[4] by Balzarotti and Grandolfo on graphite[5] and Si,[6] by Matatagui, Thompson, and Cardona[7] on seventeen semiconductors having diamond (Si), zinc-blende (AlSb, GaP, GaSb, InP, InAs, InSb, ZnS, ZnSe, ZnTe, CdTe, HgSe, and HgTe) and wurtzite (ZnO, CdS, and CdSe) structures, and more recently by Iliev and Assenov on CdS at the excitonic region[8] and by Georgobiani and Fridrikh[9] on ZnS near the fundamental absorption edge. All these experiments have demonstrated that the effect of a temperature variation on the optical properties of the material corresponds to a shift of the energy threshold and to a broadening of the involved critical points. The shift of the energy gap is caused by two distinct mechanisms: the thermal expansion and the electron-phonon interaction. The broadening is only due to the electron-phonon interaction, and generally speaking this effect is small compared to the total shift. Experimental evidence, however, exists for a strong temperature modulation only of the broadening parameter at least in the case of M_1 saddle-point singularities in strongly anisotropic materials.[5]

In recent years the III-VI compound semiconductors such as GaSe and GaS have attracted considerable attention. Most of the studies have been concerned with the crystal structure,[10] the electrical transport properties,[11] and the optical properties[12] in the vicinity of and well above the fundamental absorption edge. The crystal structures of GaSe and GaS are composed of isomorphous fourfold atomic layers and differ only in the way these layers are stacked. The Se and S atoms occupy equivalent sites, and the bonding between a multiple layer is predominantly covalent with a small ionic contribution. Owing to the fact that the bonding between layers is of the van der Waals type, the optical properties are largely governed by the structure of an individual fourfold layer; most of the theoretical work on the electronic structure of these compounds has therefore been based on a two-dimensional approximation, that is, the interaction between different crystal planes has not been taken into account.[13]

In this paper we present the results obtained by