I. INTRODUCTION

The electron excitations in a two-dimensional electron gas (2DEG) are fundamentally different from that in three-dimensional systems. When the thickness of a layer where electrons are placed is smaller than both their wavelength and free-path length, the electron energy becomes quantized with a set of separated two-dimensional (2D) subbands. Therefore a single isolated electron layer presents a strong anisotropy of electronic properties: an external electric field directed parallel to the layer causes a freckle collective motion of electrons in 2D subbands (2D plasmon), while no motion of electrons occurs with a perpendicular electric field though, in this case, intersubband electron transitions may take place.1

Two types of intersubband electron excitations are known: charge-density excitations (CDE’s) and the spin-density excitations (SDE’s) whose energies differ by a depolarization energy.2,3 The energy of the SDE’s is expected to be very close to the energy of the single-particle excitations (SPE’s) in GaAs, where many-body corrections for the SDE’s are negligible.

Even a system of coupled 2D electron layers conserves these properties of a 2DEG, the difference being that when the coupling is so strong that the subband width is comparable to the depolarization energy, the intersubband electron transitions become incoherent; consequently, the charge-density fluctuations are not followed by significant macroscopic fields, and the coupling between the CDE’s and LO phonons no longer exists. Instead of this, a broad continuum of SPE’s appears. However, in this case, in addition to the electron excitations considered above, a quasi-three-dimensional plasmon appears due to the correlated motion of electrons normal to the layers (superlattice plasmon).

Intersubband CDE in 2D isolated electron layers, the intrasubband 2D plasmons, and the superlattice plasmons are accompanied by macroscopic electric fields, and thus in polar semiconductors they couple with the longitudinal-optic (LO) phonons, giving rise to coupled intersubband and intrasubband plasmon-phonon modes.2,4

Another type of coupling between continuum electron SPE’s and the discrete LO one-phonon state takes place when the excitation energy of electrons in this continuum overlaps with the energy of the LO phonon. As was discussed in Ref. 5, this discrete-continuum interference occurs due to the Fröhlich electric potential, and may be interpreted as a result of a discrete-continuum Fano-type interference.6 The experimental conditions required to observe the Fano-type coupling can be easily fulfilled in δ-doping superlattices where the occupied electron states have the form of narrow subbands well separated in energy, while the quasi-continuum consisting of broad overlapping subbands exists at energies higher than the Fermi energy. Therefore a δ-doping superlattice with the appropriate period reveals a broad continuum of single-particle excitations overlapping the LO-phonon energy thus producing conditions for the Fano interference to occur.

The ideal tool to study the Fano interference in periodical semiconductor structures is resonant Raman scattering, which enables us to distinguish the Fröhlich electron-phonon interaction. The ability of Raman scattering to study the Fano-like electron-phonon coupling was first demonstrated in bulk semiconductors7 and in periodically δ-doping GaAs,8 where the modification of the Raman spectrum of a single δ-doped structure with an alteration of the excitation energy close to resonance was shown to occur due to the Fano-like interference. However, due to the self-consistent origin of the electron potential in δ-doped structures, the resonance con-
ditions should depend strongly on the electron density. A study of this dependence should provide us new information about the Fano-like electron-phonon interference.

In this paper we systematically studied δ-doping GaAs superlattices with different electron densities. It was shown that the same conditions (the excitation energy and the electron density) cause both the resonance of Raman scattering by the CDE and the Raman resonance of the resulting line produced by the Fano interference. Thus the importance of the Fröhlich-type electron-phonon interaction in the Fano coupling was confirmed. A comparison between the off-resonance Raman scattering and the in-resonance one allowed us to separate the coupling of the LO phonons with the intrasubband (superlattice) plasmon from the Fano-like electron–LO-phonon coupling. The Fano resonance was shown to occur with an alteration of both the excitation energy and the electron density.

Following Refs. 6 and 8, the Raman cross section can be represented by the formula

$$\sigma(\omega) = \sigma_d(\omega) + \sigma_e \frac{q^2 - 1 + 2q\epsilon}{1 + \epsilon^2}$$

(1.1)

where $\sigma_d(\omega)$ and $\sigma_e$, respectively, are a background Raman cross section and the amplitude, $\epsilon = (\omega - \omega_{LO} - \Delta\Omega)\Gamma$ is the reduced energy, where $\omega_{LO}$ is the LO-phonon frequency, and $\Delta\Omega$ and $\Gamma$, respectively, are a line shift (with respect to the unperturbed bulk LO phonon) and a linewidth parameter, which are determined by the strength of the Fano interference.

The parameter $q$ which determines the line profile is given by

$$q = \frac{2}{\pi\Gamma} \frac{P_r}{P_e} \frac{E_{g}^* - h\omega_{LO}}{(E_{g}^* - h\omega_{LO})^2 + \gamma^2}$$

(1.2)

where $P_r$ and $P_e$ are the transition probabilities from the ground state to the renormalized discrete phonon state and to the unperturbed single-particle electron continuum states, respectively, $E_{g}^*$ is the "effective" energy gap, $h\omega_{LO}$ is the excitation energy, and $\gamma$ is the broadening parameter which includes the quantum-mechanical broadening of the electron states participating in the Raman process.

II. EXPERIMENT

The samples here studied were periodically δ-doped GaAs structures grown by molecular-beam epitaxy on (100)-oriented GaAs substrates. The δ layers doped with Si were separated by $d = 300$ Å and repeated 50 times. The nominal sheet doping densities ($N_D$) varied from $1 \times 10^{12}$ to $11 \times 10^{12}$ cm$^{-2}$ as determined during the growth were used as the sheet electron densities. Probable, this overestimates the values of electron concentrations; however, this should not strongly influence the electron concentration dependencies which will be discussed later in this paper.

The Raman spectra were performed in the backscattering geometry at $T = 10$ K using a double grating JY-U1000 spectrometer supplied with a conventional photon-counting system. The 5145-Å line of an Ar$^+$-ion laser was used for off-resonance excitation, while close to the $E_0 + \Delta_0$ resonance of GaAs a DCM-DYE laser was utilized. In order to obtain the

![FIG. 1. The electronic band structure of the δ-doping GaAs superlattice with $d = 300$ Å vs the sheet doping concentration. The zero energy is taken at the bottom of the well. The full thick line and the broken one show the positions of the energy corresponding to the top of the barrier ($V_0$) and the Fermi energy ($E_F$), respectively.](image)

resonance profiles all the Raman spectra were calibrated with respect to the reference Raman scattering by the optical phonons in Si crystal which was mounted in the cryostat together with the δ-doping superlattices.

III. RESULTS AND DISCUSSION

The electronic band structure of the δ-doping GaAs superlattices used in this work was calculated by means of a self-consistent standard procedure. The plot of electron energies versus the sheet doping concentration for the structure with $d = 300$ Å is displayed in Fig. 1. According to these calculations, one-electron transitions from the lowest occupied minibands to the empty quasicontinuum states above the Fermi level occur in a wide energy interval. This quasicontinuum of SPE’s overlaps with the energy of the LO phonon over the complete range of relevant electron densities of the samples; thus at appropriate conditions we expect to observe the influence of Fano-type interference in all the samples.

As was mentioned above, the Fröhlich electron-phonon interaction is responsible for the Fano interference. Therefore, in order to obtain evidence of the Fano coupling, we measured both the resonant Raman spectra (when as it is known the Fröhlich interaction mostly contributes) and the off-resonant ones (when the deformation potential is important and the plasmon–LO-phonon coupling may be observed).

The off-resonant Raman spectrum measured for one of the samples with $N_D = 5 \times 10^{12}$ cm$^{-2}$ in the parallel $z'(x', y')z$ configuration (where $x'[110]$, $z[001]$) is shown in Fig. 2(a). It presents the line which corresponds to the plasmon–LO-phonon mode ($L'$) arising from the coupling of electrons with the LO phonons both propagating normal to the layers. The position of this mode agrees well with the calculations presented in Ref. 10. The line found around 295 cm$^{-1}$ is assigned to the LO phonon of bulk GaAs originating from the depletion layer near the surface of the sample.
The parallel polarized Raman spectrum of the same sample measured close to the $E_0 + \Delta_0$ resonance of GaAs [Fig. 2(b)] reveals a broad line attributed to the intersubband charge-density electron excitations. SDE’s are active in the cross-polarized spectrum, where a line at a slightly lower frequency was detected. This difference found between the CDE and SDE peak positions shows that, contrary to the supposition used in Ref. 5, the depolarization fields which accompany the intersubband electron excitations are important even in $\delta$-doping superlattices. Such an influence of the depolarization effect has been found in the periodically $\delta$-doped GaAs by cyclotron resonance as well.

An additional asymmetrical line denoted as LO$\gamma$ with the frequency slightly above the LO-phonon frequency of GaAs was found in the parallel polarized resonant Raman spectrum. This line was not observed either in the off-resonant Raman spectra or in the resonant cross-polarized ones. Therefore, unambiguously the origin of this line is the Frohlich electron-phonon interaction. This line can be attributed to the Fano effect. Additional proof of this origin was obtained when Raman spectra were measured close to the resonance with different excitation energies. According to Eq. (1.2), the profile parameter $q$ changes its sign when the excitation energy passes through the $E_{\gamma}^s$ gap; with $h\omega = E_{\gamma}^s$ $q=0$, the resonance profile has a form of a ‘scattering window’ (an antiresonance), while at any finite value of $q$ the asymmetric Fano peak should be observed. Antiresonance behavior can be found even far enough from the Fano resonance where $q=0$. Since $q$ is a measure of the transition probabilities to the one-phonon state modified by the electron-phonon interaction and to the single-particle electron continuum states, we expect to observe an extreme value of $q$ when the electron-phonon interaction is close to its maximum. The modification of the Fano line with an alteration of the excitation energy, which changes the role of the Fröhlich electron-phonon interaction, is presented in Fig. 3, where the resonance behavior was obtained with the laser energy close to the $E_0 + \Delta_0$ gap in the sample under investigation, while the antiresonance was found with a little lower excitation energy. The increase of the Raman intensity observed in the low frequency range of the spectra is caused by the DYE laser line.

Due to the self-consistent origin of the electron energy spectrum in $\delta$-doping superlattices, the $E_\gamma^s$ gap should depend on the electron density. Hence, a similar modification of the Fano line (from a resonance to an antiresonance) can be obtained by keeping the excitation energy constant and varying the electron density. Such a behavior of the Fano profile is clearly demonstrated in Figs. 2(b) and 3, where Raman spectra of two samples with different electron densities ($1 \times 10^{12}$ and $5 \times 10^{12}$ cm$^{-2}$), which were measured with the same excitation energy ($h\omega_L = 1.92$ eV) close to the resonance, are depicted.

The broken lines in Figs. 2(b) and 3 are the calculated with Eq. (1.1), where $\sigma_F(\omega)$ includes a broad Raman line caused by the CDE which was fitted by a Gaussian profile. We did not take into account the electron density of states in Eq. (1.1), since the spectral width of the CDE was much larger than those of the Fano line. The fitting of the calculated Raman spectra to the experimental ones allowed us to obtain the intensities of the Fano peaks ($\sigma_\gamma$) and the line profile parameters ($q$) in all the samples. For the set of structures used in this work the linewidth parameters ($\Gamma$) and the line shifts ($\Delta\Omega$) were obtained in the intervals 2–6 and 0–3.5 cm$^{-1}$, respectively.

The dependencies of the intensities of both the Fano line and the Raman scattering due to the CDE on the excitation energy and the electron concentration are plotted in Figs. 4 and 5. In the case of CDE we analyzed the total area of the Raman lines to obtain the dependencies shown in Figs. 4 and 5. The maximum of these dependencies occur at $h\omega_L = E_0 + \Delta_0$. The maximum of the Fano line intensity takes place at the same excitation energy (or electron density) as that of the CDE; this means that the Fröhlich interaction potential is responsible for both the lines. The broken lines in Figs. 4 and 5 are Lorentzian profiles fitted to the experimental points. The positions of maxima of the resonant
Raman profiles for both the CDE and Fano lines were found at the exciting energy $E_L = 1.91$ eV, which is higher than the $E_0 + \Delta_0$ gap in bulk GaAs ($1.85$ eV). Even if we take into account that the Raman resonance is due to the outgoing channel, the resulting peak positions in Fig. 4 should be at $E_0 + \Delta_0 + \hbar \omega_{\text{CDE}} = 1.89$ eV, which is still lower in energy than what is obtained in the experiment.

In our opinion the difference observed between the expected peak position of the resonant Raman profiles and the measured ones is caused by the Franz-Keldysh effect due to the spatial separation of electrons and holes in $\delta$-doped superlattices. This separation produces macroscopic electric fields in the vicinity of the wells, giving rise to a penetration of the hole wave functions into the wells and thus enlarging the $E_0 + \Delta_0$ gap.

The dependence of the Fano line profile parameter $q$ on the excitation energy, measured for one of the samples depicted in Fig. 6(a), clearly presents a resonance behavior with the resonance position close to that at which the Raman resonances of the CDE line and for the Fano one appear. This result again confirms the role of Frohlich electron-phonon interaction in the Fano effect. The least-square fitting of the $q(E_L)$ resonance curve shown by the broken line in Fig. 6(a)] was done with the phenomenological expression (1.2) with $\gamma = 15$ meV.

A similar resonance behavior was observed for the $q(N_z)$ dependence plotted in Fig. 6(b); again a resonance position was found close to the values of the electron densities at which the Raman resonances of the CDE and the Fano effect occur.

It should be mentioned that contrary to the case of the doped bulk Si, where a negative shift of the LO phonon, renormalized due to the Fano-like interference, has been found, our study of $\delta$-doped GaAs superlattices reveals a positive shift. This difference can be due to the coupling of the LO phonons with macroscopic depolarization fields of the CDE already found in the $\delta$-doped structures studied here, which was not so important in bulk Si. The small increase of the Fano line shift ($\Delta \Omega$) with increasing electron densities observed in the Raman spectra shows that in $\delta$-doping GaAs superlattices the depolarization effects lead to an even stronger line shift in comparison with that due to the Fano-like electron-phonon coupling.

**IV. CONCLUSION**

The coexistence of two different types of electron (intrasubband and intersubband)–LO-phonon interactions in
δ-doping GaAs superlattices was experimentally demonstrated using Raman scattering: the coupled superlattice plasmon–LO-phonon modes appear in the off-resonant spectra, while both types of interactions between the LO phonons and the intersubband excitations, those of the Fano type and those due to the depolarization field effects, were found close to the $E_0 + \Delta_0$ resonance of GaAs. The resonant behavior of the Fano interference between electron and phonon excitations was found to be dependent on both the excitation energy and the electron density. In addition, the Franz-Keldysh effect caused by the spatial separation of electrons and holes was found to be responsible for a shift to higher energies observed at the resonant Raman profile maximum.

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