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NEW DEVELOPMENTS IN SOLID STATE PHYSICS

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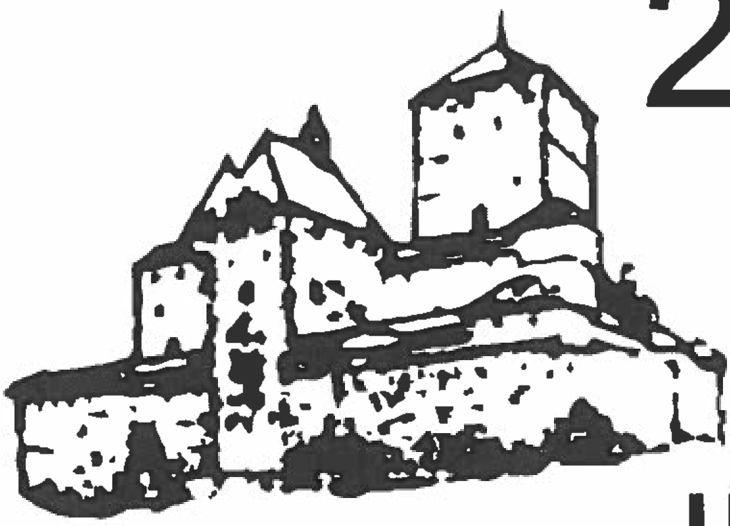

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Resonant Intersubband Plasmon Enhanced Current Transport

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Many-body interactions between electrons in quantum wells (QWs) can strongly modify intersubband transitions, leading to a creation of collective phenomena that may change electrical and optical properties of semiconductor heterostructures [1,2]. An intersubband plasmon (ISP) is a collective charge density excitation that arises due to the coupling of electrons from two different subbands. Dynamical screening and long-range Coulomb interactions between the electrons lead to a shifted single-particle transition energy, which is also known as the depolarization shift [3].

We study the coupling of two ISPs in an $In_{0.05}Ga_{0.95}As$ QW, which are tuned into a common resonance via depolarization shifts. The depolarization shifts can be either positive (blue-shift) or negative (red-shift), depending on the populations in the subbands. In order to satisfy the resonance condition $\Delta E_{32} = \Delta E_{21}$, the ground state E_1 and the highest subband E_3 have to be populated, while the second subband E_2 should be empty. These requirements can be fulfilled by current injection via a resonant tunneling diode (RTD) into E_3 and extraction from E_2 by tunneling through the triangular shaped $In_{0.05}Ga_{0.95}As/GaAs$ interface (see inset in Fig. 1). Electrons in the ground state are usually trapped, since the only way to escape is through the second subband. However, if the ISPs are resonantly coupled, these trapped electrons receive excess energy from electrons going from E_3 to E_2, which lifts them up from the ground state to the second subband. This collective effect activates a resonant electron-electron scattering process between the involved subbands [4].

This resonant ISP effect increases the total current by 33% and can be directly observed in the current-voltage characteristics. By applying a magnetic field parallel to the growth direction the e-e scattering process gets suppressed due to the quantization of the parabolic in-plane energy states into discrete Landau levels. With increasing magnetic field, the resonant intersubband plasmon process is reduced and above some critical B-field the additional current contribution vanishes. This breakdown of the e-e scattering process is clearly visible in the differential conductivity (Fig. 1). At zero magnetic field (black line), a strong dip occurs at 40mV, which decreases with higher B-fields and finally disappears at $B \approx 2$ T. The strong increase of the current suggests a major influence of collective excitations on intersubband transitions. Controlling the e-e scattering rate allows to favor or block specific transitions, which is important for devices operating below the LO-phonon energy.

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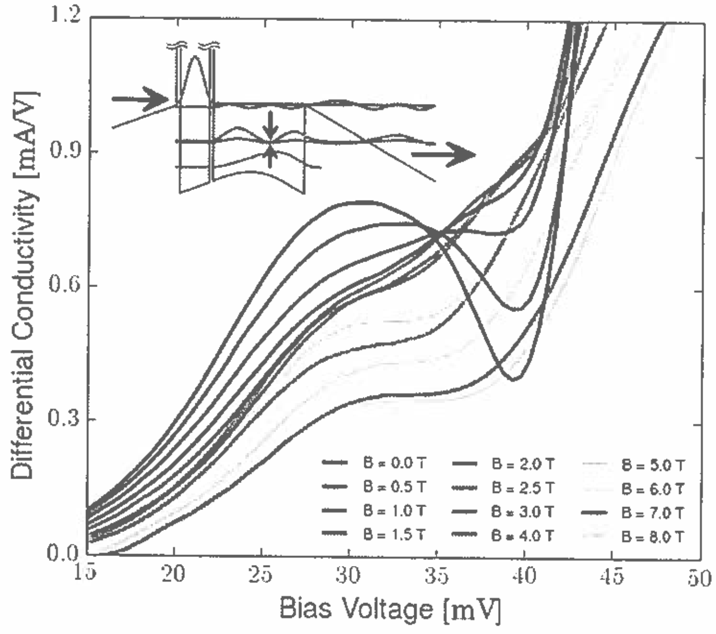

Fig. 1: Differential conductivity as a function of magnetic field applied parallel to growth direction. At zero magnetic field, a strong dip occurs at 40mV, which decreases with increasing B-field. The resonant e-e scattering process vanishes for B > 2 T, which indicates the breakdown of the collective effect. The inset schematically shows the injection of the RTD into the $In_{0.05}Ga_{0.95}As$ QW, where the second subband is depopulated via tunneling.

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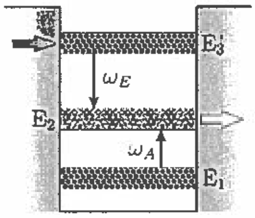
Introduction

Collective excitations of electrons in quantum wells (QWs) can strongly influence intersubband transitions by many-body interactions. One kind of such an excitation is the intersubband plasmon (ISP), which is a collective charge density excitation. In contrast to single-particle transitions, an ISP is caused by mutually coupled electrons from multiple subbands. An interesting effect arises, when two ISPs are coupled together under certain conditions. The coupling of an emission and an absorption ISP mode activates a resonant electron-electron scattering process that can be directly observed in the current-voltage characteristics.

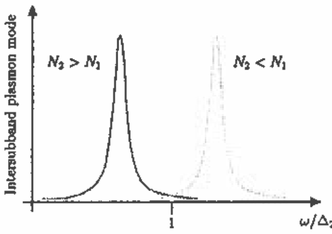
Plasma Instabilities in Quantum Well Structures

The attractive crossing of two ISP modes has been proposed as a new source for THz radiation. The simplest case is a 3-band system, where the highest level and the ground state are populated, while the second state is empty. If the subband spacings are equal ($\hbar\tilde{\omega}_{32} = \hbar\tilde{\omega}_{21}$), growing plasma waves (plasma instabilities) can build up. This hybrid excitation involves single electron scattering between the subbands and a collective excitation of all electrons in the QW.

Tuning via Depolarization shifts

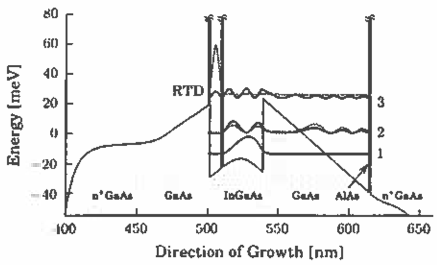


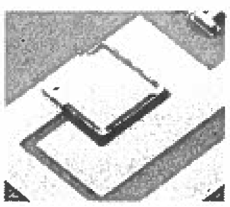
- For a normal population $N_1 > N_2$, where N_1 is the number of electrons in the lower state and N_2 in the upper state, the depolarization shift is positive and the transition energy is greater (blue-shift) than the single-particle transition energy ($\hbar\tilde{\omega}_{21} > \Delta E_{21}$).
- In the opposite case of population inversion $N_2 > N_1$, this shift is negative ($\hbar\tilde{\omega}_{21} < \Delta E_{21}$) and the intersubband plasmon mode is shifted to lower frequencies (red-shift). This depolarization shifts bring two ISP modes into resonance.



Design of the Heterostructure

The active region consists of a $In_{0.05}Ga_{0.95}As$ QW, which is sandwiched between a resonant tunneling diode and a GaAs drift region. In this configuration three subbands are coupled via intersubband plasmons, each corresponding to a pair of subbands ($3 \leftrightarrow 2$ and $2 \leftrightarrow 1$). To fulfill the resonance condition $\Delta E_{32} = \Delta E_{21}$, the ground state has to be populated with electrons and between the upper two subbands a population inversion is necessary. Tuning the external bias leads to current injection or scattering from higher levels into subband 3. Electrons from subband 2 are extracted via tunneling through the triangular shaped InGaAs/GaAs transition region. The energy difference between subband 3 and 2 is designed to be slightly larger than between 2 and 1 to account for the depolarization shifts.





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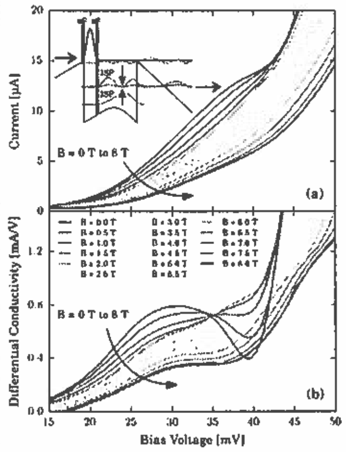
Magnetic Field Dependence

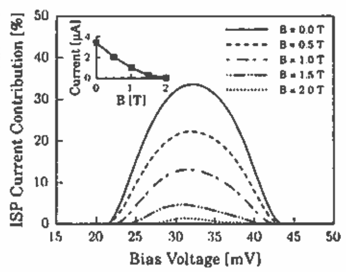
A magnetic field, applied parallel to the growth direction, quantizes the parabolic in-plane energy states in the $In_{0.05}Ga_{0.95}As$ QW into a ladder of discrete Landau levels $E_{n,l} = E_n(k_\perp = 0) + \hbar\omega_c(l + 1/2)$, where $k_\perp$ is the in-plane momentum, n denotes the subband, $\omega_c = eB/m^*$ is the cyclotron frequency and $l = 0, 1, 2, ...$ is the Landau level index. This allows to directly control intersubband scattering mechanisms by quenching the free in-plane motion of charge carriers.



- Current-voltage measurements are performed with a $100 \times 100 \mu m^2$ mesa device at 4.2 K
- A strong current increase for low magnetic fields ($B < 2T$) in the range between 20 – 40 mV can be observed.
- The collective effect activates a resonant electron-electron scattering between subbands 3-2 and 2-1.
- The dip at 40 mV in the differential conductivity marks the end of the common resonance of the two intersubband plasmons

Electrons in the ground state are usually trapped, since the only way to escape is through the second level. However, if the ISPs are resonantly coupled, these electrons receive excess energy from electrons going from E_3 to E_2. This lifts them up into the second subband, where they can contribute to the current. In contrast to single-particle scattering, this effect involves two electrons, which are part of the collective interaction between two ISPs. The effect is absent above $B \approx 2T$, which indicates that the electron-electron interaction is completely suppressed.

Intersubband Plasmon Current Contribution



- At zero magnetic field a resonant electron-electron scattering contribution of about 33 % is observed in the total current.
- However, this part drastically shrinks with increasing magnetic field and completely vanishes for fields above 2 T.

Outlook

The strong increase of 33 % in the current by resonant electron-electron scattering suggests a major influence of collective excitations on intersubband transitions. Controlling the e-e scattering rate allows to favor or block specific transitions, which is important for devices with separations below the LO-phonon energy.

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