Strong Coupling of Intersubband Resonance In A Single Triangular Well To A THz Metamaterial

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***Abstract*—We investigate the strong light-matter interactions of intersubband resonances (ISRs) in a triangular quantum well to a THz metamaterial. The large tuning possibility of ISRs with a high quality epitaxial gate enables the device to be electrically driven in-and-out of the coupling regime.**

I. Introduction

With the advent of artificial metamaterial structure, resonators with sub-wavelength sizes that have desirable properties can be integrated into semiconductors. Very recently, ultrastrong coupling experiments have been performed where the cyclotron resonance (CR) of a two-dimensional electron gas (2DEG) is coupled to THz split-ring resonators (SRRs) [1] by tuning the CR with an external magnetic field. However, electrical tunability is more desirable in such studies for both fundamental research and device applications. Gabbay et al. [2] have modelled the coupling of metamaterials to tunable intersubband resonances (ISR) in a quantum well for mid-infrared frequencies, which has been demonstrated by Benz et al. [3]. To excite ISR, polarization selection rule necessitates a component of the incident electric field in a direction parallel to the growth axis. Use of metamaterials not only avails a strong in-plane field but also a significant electric field in the growth direction due to local bending of the field around the meta-atoms [4], thus coupling the free-space THz radiation to excite the ISRs in 2DEG.

In this contribution, we use the wide electrical tunability of the ISR in a single heterostructure with a triangular confining potential. We present experimental results on strong coupling of the 2DEG ISR to a fixed cavity resonance of THz metamaterial. This is performed by electrically tuning the ISR by applying bias on the epitaxial gate and thus driving the device from an uncoupled regime to a strongly coupled regime and again back to the uncoupled regime. The tuning of the ISR is attributed to the quantum confined Stark effect.

II. Results

The device is based on intersubband transitions in 2DEG, formed in a GaAs/AlGaAs heterojunction with a triangular confining potential, typically in the THz regime. Due to the presence of strong built-in electric fields in the inversion layers of GaAs/Al$_x$Ga$_{1-x}$As heterojunction, the electronic motion perpendicular to the surface is quantized, resulting in the formation of quasi-two-dimensional-subbands. The spacing between these subbands are in the order of a few terahertz. A metasurface of electronic double split-ring resonators of sub-wavelength sizes (see fig. 1(a)) is designed to have a cavity resonance comparable to the spacing between the ground subband and the first excited subband in the 2DEG. The structures are processed by conventional UV-photolithography, evaporation of Cr/Au (10/200 nm) and lift-off technique.

Electromagnetic field distributions performed by finite difference time domain software not only show strong enhancement of the in-plane field, fig. 1(b)) but also a strong distribution of the out-of-plane field in the growth direction (fig. 1(c)) resulting from the fringing effect on the surface [4]. This ensures that the vacuum field effectively couples to excite the intersubband transitions in the quantum well. The frequency response of the metamaterial is characterized at room temperature by THz time domain spectroscopy. Two

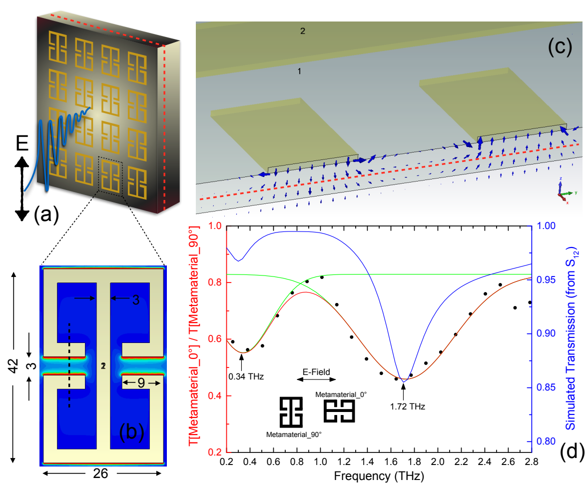

Fig. 1. (a) Schematic of the sample with metamaterials (all dimensions in μm) deposited on top and the 2DEG layer, which is 162 nm below the surface, shown by the red-dashed line. The electric field polarized in the vertical direction, as indicated schematically, couples to the metamaterials to excite the resonance. (b) In-plane electric field distribution below the metamaterials. (c) The fringing field distribution, in the growth direction along the cut, indicated by the black-dashed lines in (b). The red-dashed line represents the position of the 2DEG layer. (d) The measured transmission curve plotted in red shows two dips at 0.34 THz and 1.72 THz. The corresponding simulated transmission is plotted in blue, which shows very close agreement.

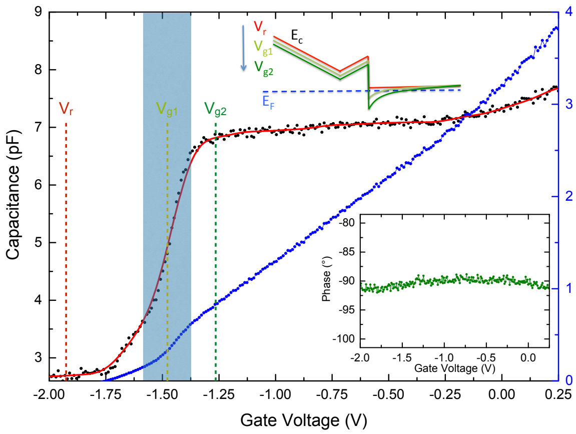

Fig. 2. The change in capacitance as a function of the applied gate voltage. The steep increase in capacitance indicates the filling of 2DEG subbands with electrons. The blue curve indicates the change of 2D carrier density with the gate voltage. A schematic of the band allignment depending on the bias is shown corresponding to three points (indicated by dashed lines) on the charging curve, each of which are color-coded. Inset: The phase over the complete range of measured gate voltage.

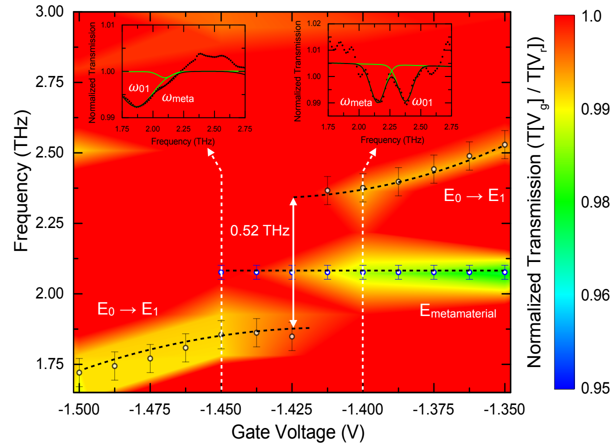

Fig. 3. Contour plot of the density-chopped THz transmission spectra which shows avoided crossing at the point when the resonance frequency corresponding to the transition from the ground to the first excited subband is equal to the resonance frequency of the metamaterials. Inset: The individual transmission spectra for two voltage points as indicated by the white-dashed lines.

dips are observed in both the simulated and the experimental transmission curves at 0.34 THz and 1.72 THz (see fig. 1(d)). At low temperature the transmission dip at 1.72 THz shifts to 2.01 THz. This is due to the fact that at low temperature the radiative damping of the cavity and losses decrease, thus blue-shifting the resonance.

The charging of 2DEG subbands in the triangular quantum well is characterized by capacitance-voltage spectroscopy. The steep slope in the capacitance, shown in fig. 2, indicates the filling of the 2DEG subbands with electrons as the gate voltage is increased. It is ensured that all the donor-exchange (DX)-centres are ionized by illuminating the sample. The blue shaded region in fig. 2 indicates the voltage range over which the density-chopped THz transmission spectroscopy is performed. The contour plot of the density-chopped transmission spectra is shown in fig. 3, where an avoided crossing is observed at 2.1 THz.

The 2DEG and metamaterials in our device can be considered as two oscillators, one of which has a fixed frequency and the frequency of the other oscillator (2DEG) is tuned by the gate voltage. When the frequencies of both the oscillators are similar, they form a coupled system and an anti-crossing phenomenon is observed, shown in fig. 3. This results in a periodic transfer of energy between the 2DEG and the microcavity through vacuum Rabi oscillations, which is proportional to the splitting at the anti-crossing point. Using the common oscillator model, described by Gabbay et al. [2], the strength of the coupling, Ω, is found to be 0.52 THz. The observed splitting is a significant fraction of the intersubband resonance in the triangular uantum well which indicates a strong light-matter interaction at the avoided crossing. The normalized coupling ratio (Ω/ω_0) is found to be 0.26. In our experiments, we limit the bias applied on the gate to -1.3 V. Since with increasing bias, the slope of the triangular confinement becomes steeper, the second subband is pulled below the Fermi level, which makes the transition scheme different and is not desirable. The asymmetric triangular potential in our device leads to a wide electrical tuning of intersubband resonances in the quantum well, which is an order of magnitude higher as compared to an equivalent square well. In addition, we have also observed a significant modulation of the strength of the cavity resonance by applying bias on gate.

III. Conclusion

In conclusion, we have demonstrated strong coupling of the 2DEG ISR to a fixed cavity resonance of a terahertz metamaterial. We show that the triangular well has an advantage over the square well since the tuning parameter of a triangular well is one order of magnitude higher than a similar square well.

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