RESONANT TERAHERTZ PHOTOCONDUCTANCE OF GRATING GATED DOUBLE QUANTUM WELL FIELD EFFECT TRANSISTORS

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ABSTRACT

Coupled double quantum well field effect transistors with a grating gate exhibit photoconductive response that resonates with standing 2-D plasmons under the gate. Readily tuned resonances occur around ~600 GHz. The response is relatively broad and uninspiring at ~ 4 K but grows and sharpens dramatically ("Q" 20) as the temperature is raised to ~ 20-40 K. The detection mechanism is not clear but we have confirmed that the resonance is controlled by the standing plasmons under the grating gate and that a coupled double quantum well is required. The role of the coupled double quantum wells is underscored by a dramatic inversion and shift of the photoconductive plasma resonance by an in plane magnetic field. Current measurements can only determine that the response time is less than 700 nsecs. The prognosis for developing a fast tunable incoherent detector or heterodyne detector will be discussed.

INTRODUCTION

The exploration of the terahertz region of the electromagnetic spectrum is limited by appropriate source and detector technology. Tunable solid state sources and detectors are key to the development of this part of the spectrum. There are a variety of terahertz incoherent and coherent detectors - hot-electron bolometers[1, 2, 3], composite bolometers, superconducting-insulator-superconducting junctions[4, 5], pyroelectric detectors[6], Schottky diodes[7, 8] and photoconductive detectors. Tunablity is a feature that can distinguish a class of incoherent detectors. In this work we explore the potential of developing incoherent detectors tuned by plasmon resonances in double quantum well field effect structures. Double quantum well structures form a bilayer system of two dimensional electron gases. Such a system has two plasmon modes that correspond to the charge density oscillations in each layer being in-phase (optic plasmon) and out-of-phase (acoustic plasmon). These modes have been studied theoretically[9, 10] and experimentally[11, 12] but, to our knowledge, no attempt has been made to develop a detector based on them. We report the terahertz photoconductivity of double quantum well field effect devices in which the gate is a periodic metallic grating. Strong photo-response occurs at the plasma resonance, which is controlled by both the voltage applied to the gate and the period of the grating gate[13].

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EXPERIMENTAL DETAILS AND RESULTS

Sample Structure

The field effect devices are fabricated from modulation doped GaAs/AlGaAs double quantum well heterostructures. The wells are 200Å wide with a 70Å barrier. The nominal electron densities in the quantum wells are $n_{upper}=1.7\times10^{11}cm^{-2}$ and $n_{lower}=2.57\times10^{11}$ cm^{-2}: the 4.2K mobility is ~1.7×10^{6} cm^2/Vs. The material is processed into a $2\times2mm^2$ mesa and ohmic contacts to both quantum wells form the source and drain. A 700Å thick metal grating gate is evaporated with the grating parallel to the ohmic contacts, perpendicular to the current flow. The grating serves to 1) modulate the electron density by acting as a gate, 2) produce a component of the terahertz electric field normal to the layers and 3) select the wavevector of the excited plasmon. Grating periods of 4 and 8 μm were explored; half the period is metal.

Measurement Technique

In order to measure the terahertz photoresponse, the samples are wire bonded and placed inside a variable temperature cryostat. We apply a constant source-drain current of 100μA, focus the terahertz radiation onto the sample and study the photoconductive response of the double quantum wells as a function of gate voltage, temperature and terahertz frequency. The radiation sources are the free-electron lasers at UCSB, which cover a frequency range between 120 GHz and 4.8 THz. Results were obtained in the low power limit by assuring that the response was a linear function of incident power.

Results:

Temperature Dependence

The terahertz photoresponse as a function of gate voltage at various temperatures for a radiation frequency of 570 GHz is shown in Figure 1. At T=2.2K the photoresponse shows a broad maxima, peaked around Vg~-1.19V. As we increase the temperature, the peak narrows, increases in magnitude and shifts to higher gate voltages (lower electron densities). This trend continues up to T~40K, after which the resonant response decreases and broadens. At T=80K it is back down to the size it had at T=2.2K.

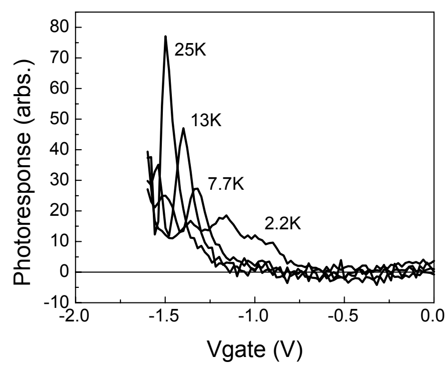

Figure 1: *Terahertz photoresponse at 570 GHz for four different temperatures. Note the narrowing and increase in magnitude as the temperature increases. Grating period is 4μm.*

Frequency and Grating Period Dependence

Figure 2 shows the terahertz photoresponse as a function of gate voltage and frequency, at 25 K, for two different grating periods: 4μm (left) and 8μm (right). We observe that both grating periods show a resonant response that moves to lower gate voltage, higher electron density, as we increase the frequency (see guiding symbols for the 8μm grating period). This follows the expected dispersion relation for plasmon modes in double quantum well systems. Note that the larger the period, the greater the number of allowed standing waves in a frequency interval. For a given excitation frequency, a larger number of resonances will appear in a gate voltage range, corroborating the idea that the observed resonant response is caused by the standing plasmon modes and its spatial harmonics underneath the grating metallization.

The precise mechanism for the change in conductance is not understood but we have determined that we require two quantum wells. The photoresponse of a single quantum well processed in an identical manner exhibits no resonances; the change in conductance at resonance with the standing plasmon is conditioned on the presence of the double quantum well in the ungated part of the device.

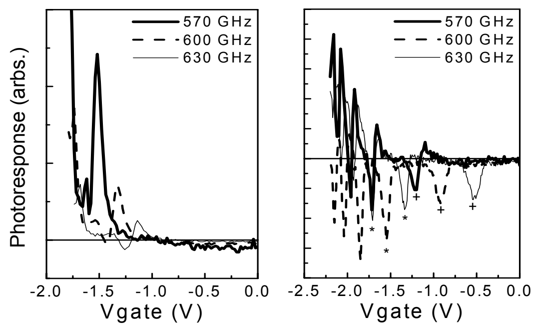

Figure 2: *Terahertz photoresponse as a function of gate voltage at T=25K for three different frequencies and two different grating periods: 4μm (left) and 8μm (right). Note the higher order modes present in the 8μm period grating. The * and + symbols indicate which peaks to follow as a function of frequency.*

The ability to tune the resonance by means of the gate voltage or the grating period allows for the possibility of developing tunable incoherent detectors for the terahertz range.

In-Plane Magnetic Field Dependence

Applying an in-plane magnetic field causes an inversion, an increase of the photoconductive plasma resonant response as well as a shift in the resonant gate voltage position (see Figure 3). There is no change in the linewidth or lineshape of the resonance.

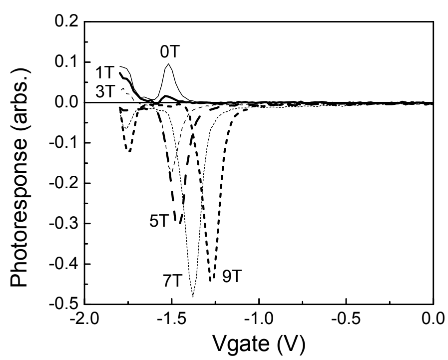

Figure 3: *Terahertz photoresponse as a function of gate voltage at various different in-plane magnetic fields (T=25K, frequency = 570GHz, grating period 4μm).*

Time Response and Responsivity

We have also measured and compared the time response of the 4μm period grating double quantum well field effect transistor at resonance (frequency = 570 GHz) and the fast pyroelectric detector used as a reference. From those measurements we can say that the devices' response time is less than 700 ns; the measurement is limited by the free electron lasers' rise and fall time.

An estimate of the noise equivalent power, NEP and responsivity yield $6\mu W/Hz^{1/2}$ and R=890μV/W, respectively. These estimates are fixed at the entrance to the cryostat and include transmission losses, coupling to the device and other extrinsic factors that can be mitigated to some extent. Nonetheless these figures indicate that substantial improvements are needed to begin to compete with good incoherent detectors.

DISCUSSION

We have observed a resonant photoresponse in coupled double quantum well field effect transistors corresponding to the excitation of standing plasma waves under the metallic part of a grating gate. The resonance can be tuned by means of a gate or by changing the period of the grating gate. While we understand that the tunable resonance is caused by the composite plasma oscillations, the mechanism that gives rise to the change in conductance at resonance is not understood. It is conditioned on the presence of the double quantum well, a conclusion supported by the effect of an in-plane magnetic field on the response. There are several issues that remain to be addressed - the temperature dependence of the amplitude and linewidth, the sign reversal with grating period, lineshape variation with frequency and physical effect of the in-plane magnetic field. Its use as a tunable incoherent detector requires substantial improvement in NEP. On the other hand the response time has been measured to be no slower than 700 ns. It is a low impedance device and further measurements may open the possibility of using the device as a heterodyne detector with IF electronics integrated on the same chip.

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