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Terahertz detection in a double-grating-gate heterotransistor

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Abstract. We observed a photovoltaic non-resonant terahertz photoresponse in a InGaAs/GaAs heterostructure with a large area double-grating-gate at room temperature. Semi-quantitative estimation of the characteristic detection length combined with self-consistent calculations of the electric fields exited in the structure by incoming terahertz radiation allowed us to interpret this detection as coming from the depleted regions of the channel.

1. Introduction

It is known that hydrodynamic nonlinearities in two-dimensional (2D) electron channels can be used for detection of terahertz (THz) radiation [1]. Resonant THz detection is related to plasmonic nonlinearities in 2D electron channel whereas a broadband non-resonant THz detection is produced by nonlinearities of the oscillating electron currents in depleted regions of the channel where plasmon oscillations are overdamped. High external detectivity can be obtained only if high-quality plasmon resonances are excited in the resonant THz detector and strong THz electric fields are induced in depleted regions of the channel in the non-resonant THz detector. The metal-grating-gate coupler is a conventional tool for coupling plasmons in 2D electron channel to THz radiation [2]. In this paper we demonstrate non-resonant THz detection in a double-grating-gate InGaAs/GaAs heterotransistor at room temperature and interpret this detection as coming from the depleted regions of the channel.

2. Experimental

The device structure is based on a high-electron mobility transistor (HEMT) and incorporates doubly interdigitated grating gates (G1 and G2) [3]. The 2D plasmon layer is formed with a quantum well at the heterointerface between a 15-nm-thick undoped InGaAs channel layer and a 60-nm-thick, Si-δ doped InGaP carrier-supplying layer. The grating gate is formed with 65-nm-thick Ti/Au/Ti by a standard lift-off process. The metal fingers of each grating gate G1 and G2 (L_{G1} and L_{G2}, respectively)

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are of the same length but the finger lengths L_{G1} and L_{G2} are different for different grating gates G1 and G2. Four different structures with a double-grating-gate were fabricated. Grating gate G1 was designed to have fingers of length L_{G1}=100 nm in each structure, while grating gate G2 was designed to have fingers of different lengths from L_{G2}=300 nm to L_{G2}=1800 nm for different structures. The spacing between the grating-gate fingers is 100 nm for all four structures. The gate-to-channel separation is d = 65.5 nm and the threshold (depletion) voltages at gates G1 and G2 are – 3.5 V and – 3.0 V, respectively. The whole length of the structure between the source and drain contacts covered by the double-grating gate was about 80 μm with the channel width of 30 μm.

Table 1. Measured photoresponse for different samples.

Sample #	1	2	3	4	5	6	7	8
$L_{\text{G-biased}}$(nm) /$L_{\text{G-unbiased}}$(nm)	100 /1800	100 /1300	100 /800	100 /300	300 /100	800 /100	1300 /100	1800 /100
Photoresponse per period (μV)	0.5	0.4	0.6	1.15	1.8	2.1	2.3	2.85

The double-grating-gate structures were irradiated with terahertz beam at frequency 240 GHz. We measured a photovoltaic response between the source and drain contacts at room temperature. The greatest non-resonant photoresponse was observed when one of the grating gates, either G1 or G2, was biased to the threshold voltage. The photoresponse per period of the structure is shown in table 1 for eight different samples. The photoresponse grows with increasing the length of a depleted portion of the channel per the structure period (under a biased grating-gate finger) for samples ## 5-8 and also grows with decreasing the length of undepleted portion of the channel per the structure period (under unbiased grating-gate finger) for samples ## 1-4. Note that an absolute value of the photoresponse is relatively small because fabrication arrangements were not undertaken to bring designed asymmetry into the structure unit cell which had to be normally required for ensuring stronger photoresponse.

3. Discussion

The theory of non-resonant terahertz detection due to hydrodynamic nonlinearity of the 2D electron fluid has been proposed in [1] and then developed in more advanced form in [4] taking into account a finite electron temperature. However, this theory assumes asymmetric excitation of the channel, where a predefined THz electric field is applied to the input of the channel, and then describes how this field propagates along the channel producing detection photoresponse. Such theory can not be used directly for qualitative analysis of the system under study where the oscillating currents are excited in every point of the channel simultaneously by normally incident THz wave. Therefore, in this paper we use a semi-quantitative approach for describing the THz photoresponse in the double-grating-gate structure.

According to [1] the hydrodynamic nonlinearity in 2D electron channel comes from the product $n(x)v(x)$ in the hydrodynamic equation of continuity, where $n(x)$ and $v(x)$ are the oscillating electron density and velocity depending on the coordinate along the channel (x-coordinate). The oscillating electron density $n(x)$ in every x-point of the channel is proportional to the normal component of the electric field at that point, while the oscillating electron velocity $v(x)$ in every x-point is proportional to the in-plane component of the THz electric field at that point. Amplitudes of the normal and in-plane components of the electric field in the channel are proportional to each other because they are interrelated by the linear Maxwell equation (or Poisson equation in the electrostatic case). However, those components of the electric field are shifted in phase along the x-coordinate by $\pi/2$. Then assuming a harmonic dependence of $n(x)$ and $v(x)$ on the x-coordinate we can estimate this nonlinearity as $n(x)v(x) \sim |E|^2\sin(2\pi x/\Delta)\cos(2\pi x/\Delta)$, where $|E|$ is the amplitude of the normal (or in-plane) component of the electric field in the channel and Δ is the spatial period of its variation along the x-coordinate. It is known [1,4] that a non-resonant detection response comes predominantly from depleted parts of the channel. We can describe the net effect of detection coming from an active (depleted) channel portion of length w by the characteristic detection length

$$L_D = \frac{|E|^2}{|E_0|^2}\int_0^w \sin\left(\frac{2\pi}{\Delta}x\right)\cos\left(\frac{2\pi}{\Delta}x\right)dx = \frac{\Delta}{2\pi}\frac{|E|^2}{|E_0|^2}\sin^2\left(\frac{2\pi}{\Delta}w\right),$$

where E_0 is the electric field of incoming THz wave. The value of L_D exhibits maximum for $w = \Delta/4$, which means that the active part of the channel is effectively short-circuited at its one end whereas it is open-circuited at the other end.

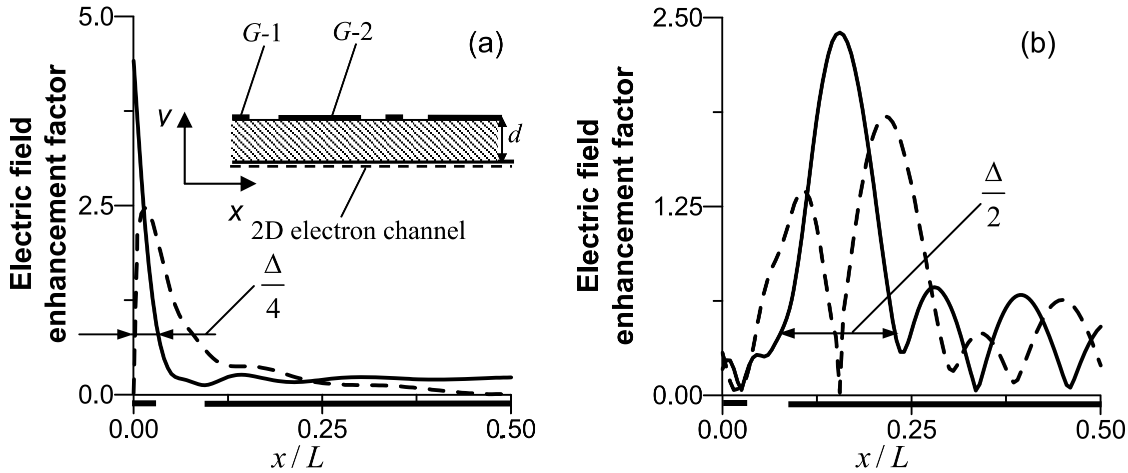

Figure 1. In-plane (solid curves) and normal (dashed curves) THz electric field distributions in the 2D electron channel for (a) sample #1 and (b) sample #8 over a half of the structure period $L/2$ at frequency 240 GHz. Inset in panel (a) shows a schematic of the double-grating-gate structure. Location of the grating-gate fingers are also indicated by thick black bars under the abscissa axes. The origin is located under the centre of the G1 finger.

We calculated the normal and in-plane electric field distributions over the structure period in a first-principle electromagnetic approach [5] for all eight samples specified in table 1. The electric field distributions for samples ## 1 and 8 are shown in figure 1. The regions of strong electric field with the electric-field-enhancement factor, $|E|/|E_0|$, exceeding unity are seen in figure 1 in depleted parts of the channel. These regions with strong electric field can be thought as having the length of $\Delta/2$. It means that each region of strong electric field can be viewed as two oppositely-connected channels, which are short-circuited at the center of this region but open-circuited at the ends of this region. Then, for samples ## 5-8 we have $w \approx \Delta/4$ and, hence,

$$L_D \sim \frac{|E|^2}{|E_0|^2}\frac{\Delta}{2}$$

in this case. Whereas for samples ## 1-4 we have $w < \Delta/4$ and, hence,

$$L_D \sim \frac{|E|^2}{|E_0|^2}\frac{2w}{\Delta}w$$

for these samples. In the last formula the ratio $2w/\lambda$ is the form-factor describing a fraction of $\Delta/2$ occupied by the active (depleted) portion of the channel. Electrostatic modeling of the equilibrium electron density distribution show that in samples ## 1-4 with the grating-gate G1 biased to the threshold voltage only very short regions under the centers of 100-nm-wide fingers are depleted. Because of that we estimated the effective length of the active (depleted) region of the channel as $w \approx 20$ nm for samples ## 1-4. Actually, this value of $w \approx 20$ nm serves as a fitting parameter to match the detection length dependencies for samples ## 1-4 and those for samples ## 5-8. Calculated detection lengths for all eight different samples shown in figure 2 demonstrate good agreement with the measured photoresponse for all samples.

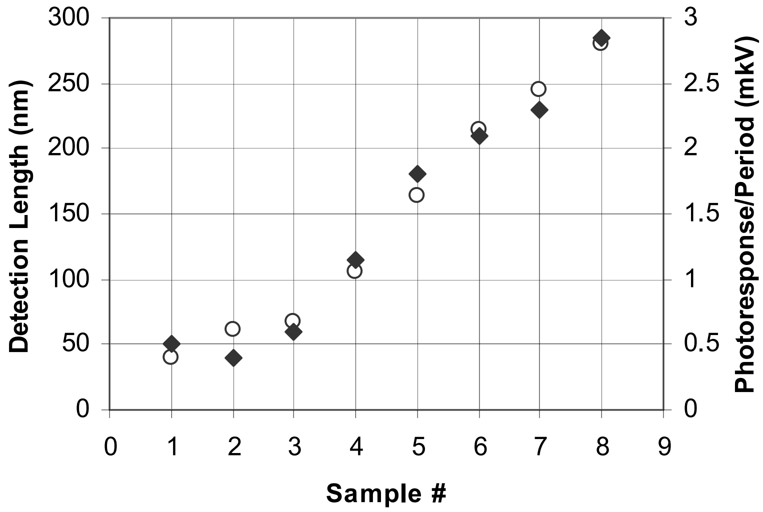

Figure 2. Detection length (open circles) and measured photoresponse (solid diamonds).

4. Conclusions

We have measured a THz photovoltaic response in a double-grating-gate InGaAs/GaAs heterotransistor at room temperature, which was interpreted as coming from depleted regions of the channel due to hydrodynamic nonlinearity. Large THz-electric-field enhancement factor achieved in the double-grating-gate structure was demonstrated. We believe that the photoresponse could be considerably enhanced by fabricating a double-grating-gate heterotransistor structure with asymmetric unit cell.

Acknowledgments

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