Large Area Self Assembled Tunable Terahertz Detector

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Abstract— **Recently compact frequency sensitive THz detection has been achieved using gated gratings on 2DEG structure. The method is based on the resonant absorption of the 2D plasmon dependence on tuning of carrier density by depletion gating. Here we demonstrate a method to improve detector sensitivity, tunability and remove polarization dependence through the development of a gated grid design. The requirement for imaging applications of device dimensions on the order of < 1 micron over a detector area of 4 mm^2, suggest that standard lithographic approaches will be too costly for large scale detector production. Here we realize the gated grid plasmonic structure on 2DEG material by using nanosphere self-assembly lithography.**

I. Introduction And Background

A plasmon is a quasi particle which is the quantized collective oscillation of a free electron gas. The Drude-Sommerfeld model starts with a semiclassical equation of motion for a single particle with the collision rate γ in a harmonic electric field with frequency ω.

$$m\ddot{x} + m\gamma\dot{x} = eE_o e^{-i\omega t} \quad (1)$$

where m is electron mass. The solution gives the equation of motion of the electron in the applied electric field. Solving equation (1) using Ansatz $x(t) = x_o e^{-i\omega t}$ and using the result of dielectric constant with the induced polarization, $\varepsilon = 1 + \frac{|P|}{\varepsilon_o|E|}$ yields

$$\varepsilon_m(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2, \text{ where } \omega_p = \sqrt{\frac{Ne^2}{\varepsilon_o m}} \quad (2)$$

in the limit as $\omega \gg \gamma = \frac{1}{\tau}$. As seen the solution has a resonance at the plasma frequency, ω_p. Using the dispersion relation in a medium, $k^2c^2 = \varepsilon_m\omega^2$ the dispersion relation of plasmon should be described as $\omega^2 = \omega_p + c^2k^2$.

By definition 2 dimensional plasmons are the quanta of surface-charge-density oscillations. 2 dimensional electron gas (2DEG) is well known as a plane electrons embedded in a dielectric. Let the plane of electrons be contained in the half space $z > 0, z < 0$. Using boundary conditions the 2-D plasmon is a solution to Maxwell's equations of the form:

$$\nabla \times \nabla \times \vec{E}(q,\omega) - \frac{\omega^2}{c^2}\varepsilon(q,\omega)\vec{E}(q,\omega) = 0 \quad (3)$$

$$\vec{E}(q,\omega) = \begin{pmatrix} E_{ox} \\ 0 \\ E_{oz} \end{pmatrix} e^{i(qx-\omega t)}e^{iq_j z}; j = 1,2 \quad (4)$$

in half space j=1 and j=2. The momentum of 2-D plasmon is related to resonance frequency as

$$q^2 = \frac{\varepsilon_1\omega^2}{c^2} + \left(\frac{\omega^2}{a}\right)^2, \text{ where } a = \frac{Ne^2}{m^*\varepsilon_2}, q = \frac{2\pi}{\lambda} \quad (5)$$

N is number of electrons per unit area, m^* is effective mass of electrons, and $\varepsilon_1, \varepsilon_2$ is dielectric constant of half space j=1 and j=2 of the medium respectively. This solution is in the regime as $qc \gg \omega$.[1]

The excitation of plasmons with light is in general forbidden, as the momentum of light is transverse to the electric field, whereas the momentum of the plasmon is parallel to the electric field. Thus, no momentum is available from the photon for the plasmon. To couple with light, we need to modulate the in-plane electric field of light so there is a momentum component of the plasmon along the same direction as the field.

First consider a bare interface and no spatial variation of electric field in x-y plane. The plane wave equation of electric field of photon is as

$$\vec{E} = E_o\hat{x}e^{i(k_z\cdot z-\omega t)} \quad (6)$$

In this case for a 2DEG placed close to the interface, there is no modulation of the in-plane electric field, and the response is free carrier Drude absorption. In a periodic metallic gratings is placed at the interface as shown in Figure 1, boundary conditions dictates that the field must be perpendicular to the conducting regions, resulting in periodic modulation of the field direction with the grating periodicity. The electric field

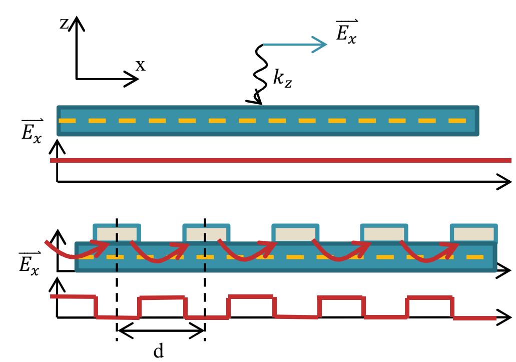

Figure 1. A toy model of electric field of light near gratings on the surface of 2DEG

wave equation can be approximated as

$$\vec{E_x} \sim E_o\hat{x}e^{i(k_z\cdot z-\omega t)}\cos\left(\frac{2\pi}{d}x\right) \sim E_o\hat{x}e^{i(k_z\cdot z+q\cdot x-\omega t)} \quad (7)$$

, where $q = \frac{2\pi}{d}$, d is an interval of grating. We can then associate a net wavevector with the incident electric field of: $k = q\hat{x} + k_z\hat{z}$ with a component of the wavevector along the same direction as electric field. In this case momentum can be conserved for surface plasmon excitation.

The relation between resonance frequency and wavevector may be approximated by

$$f_o^{\,2} = \frac{1}{4\pi^2}\frac{n_s e^2 k_j}{2m^*\epsilon_o\epsilon_1} \quad (8)$$

where e is the electron charge, n_s is the 2-D carrier density, ϵ_o is the permittivity of the dielectric below the 2DEG, ϵ_1 is the permittivity of dielectric between gate and 2DEG, m^* is the electron effective mass. We can define wave vector as $k_j = \frac{2\pi}{l}j$ where l is the grating gate period.[2] From the equation, the

length of grating gate period is inversely proportional to the 2-D plasmon resonance frequency squared. By reducing the gate period, the resonance frequency increases. We note that periodicity in the metallization is not a necessary condition for plasmonic coupling. Any metallization located in close proximity to the 2DEG will give rise to a discontinuity in the inplane electric field in the 2DEG with a wavevector expansion in $2\pi/d$, where d is the length along the direction of the field. Knap and coworkers have demonstrated that for even a single metal gate, plasmonic coupling can be achieved.

The 2-D carrier density n_s in equation (8) is can be controlled through a gate voltage with subsequent tuning of the plasmon resonance.[2]-[4] [5],[6]

To enhance the sensitivity one would want the device area to be on the order of a typical focus spot size ~2mm. While large area small period gratings are possibly using holographic lithography, the polarization dependence of these detectors again will limit sensitivity. For example for polarization independent thermal sources, grating based detectors will detect only half the incident radiation. Using a periodic grid grating with circular apertures would eliminate this polarization dependence.

II. Materials and Methods

Large area devices can easily be achieved using photolithography, however typical systems are limited to >1 micron feature size. Large area devices with submicron features could be achieved using ebeam lithography, however each device would be expensive in ebeam writing time and the density of writing may be sufficient to induce damage in the 2DEG which is only 50nm below the surface. Here we overcome the limitations by using a self-assembly technique based on nanosphere lithography. [13]

We realize large area plasmonic detection through a submicron grid fabricated using self-assembly techniques. We form a large area nanosphere monolayer on a substrate by spin coating. Using a custom built spinner, we drop cast 7~9µl polystyrene sphere solution on the 2DEG substrate. A large area self-assembled hexagonal closed pack monolayer is formed over a ~ 4 mm^2 area. If the self-assembled monolayer is used as a metallization mask without further processing, one can achieve a pattern of nanometer disconnected triangles.[13] We require a continuous metallization, both to achieve the necessary in-plane electric field modulation for coupling light to the 2D plasmons, and also for the depletion control of the 2DEG. In order to have a continuous conducting sheet with circular apertures, we use Reactive Ion Etching (RIE) of the self-assembled nanosphere monolayer to reduce the sphere size and increase spacing between spheres. RIE using oxygen at low power density etches the polystyrene spheres uniformly. A fully interconnected pattern can be achieved with a 5minute etch allowing for the entire region to be used as a gate. The sample with the etched monolayer is then placed in a thermal evaporator and 50nm of aluminum is deposited. After metallization the sample is placed in toluene and gently sonicated to lift off the nanospheres. In Figure 2, we show an image of the metallization. As seen the metal is completely interconnected. THz transmission measurements are performed using a standard THz TDS system.

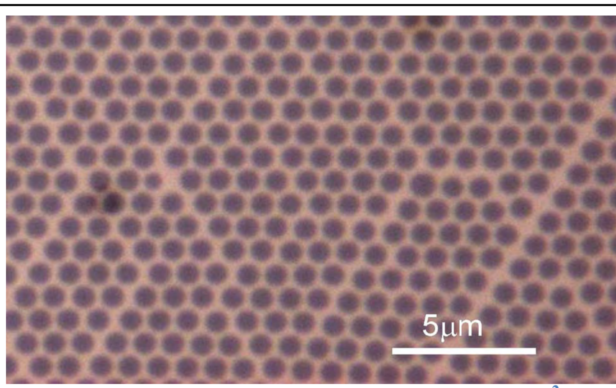

Figure 2. Micrograph of small area within the ~ 4 mm^2 plasmonic array achieved through self-assembly processing on GaAs/AlGaAs 2DEG material.

III. Results and Conclusions

Initial measurements demonstrate the plasmonic resonance for the self assembled device. In Figure 3, we show transmission measurements for the device shown in Fig. 2. Along with the measured transmission we show calculated transmission for Drude absorption for charge density $n_s = 2 \times 10^{11}$ cm^{-2} and mobilities 10, 50, and 100 k cm^2/V·s respectively. The measured transmission clearly is not following Drude response, but rather has two sharp resonances, with the feature at 0.4THz corresponding to the predicted plasmon resonance. Measurements at room temperature show a large transmission resonance and the plasmon resonance with a change in the transmission of 10%.

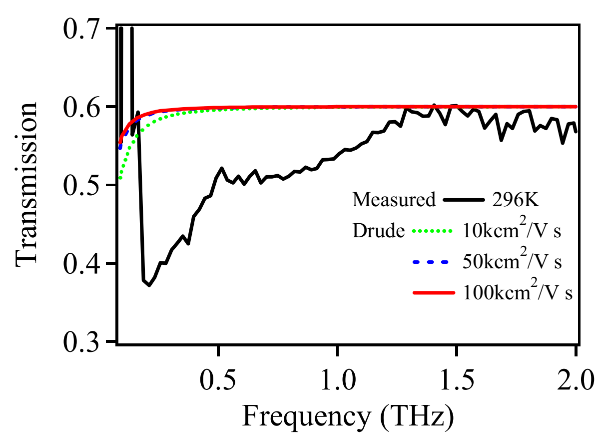

Figure 3. Transmission of the plasmonic device with the self-assembled grid at room temperature.

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