Grating-gate tunable plasmon absorption in InP and GaN based HEMTs

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ABSTRACT

Gate-voltage tunable plasmon resonances in the two dimensional electron gas of high electron mobility transistors (HEMT) fabricated from the InGaAs/InP and AlGaN/GaN materials systems are reported. Gates were in the form of a grating to couple normally incident THz radiation into 2D plasmons. Narrow-band resonant absorption of THz radiation was observed in transmission for both systems in the frequency range 10 – 100 cm^{-1}. The fundamental and harmonic resonances shift toward lower frequencies with negative gate bias. Calculated spectra based on the theory developed for MOSFETs by Schaich, Zheng, and McDonald (1990) agree well with the GaN results, but significant differences for the InGaAs/InP device suggest that modification of the theory may be required for HEMTs in some circumstances.

Keywords: Terahertz detectors, HEMT, 2deg, grating-gate devices, plasmons

1. INTRODUCTION

Present work focuses on the application of grating-coupled high-electron-mobility transistors (HEMTs) for the detection of THz radiation via tunable resonant absorption due to the excitation of plasmons in the two dimensional electron gas (2DEG) of these devices. A possible associated change in source-drain conductance is the basis of proposed frequency-agile THz detectors.[1] Sheet charge density and the characteristic length scale of the gate metallization determine the plasmon resonance frequency. Gate bias control of the sheet charge density allows continuous tuning of the resonances over a wide range. Incident THz radiation is coupled to 2D plasmons in a (HEMT) by a metallic transmission grating that also serves as the gate contact. The grating period defines the wave vector of the excited plasmon, as shown in Figure 1, where the THz radiation is incident normal to the surface.

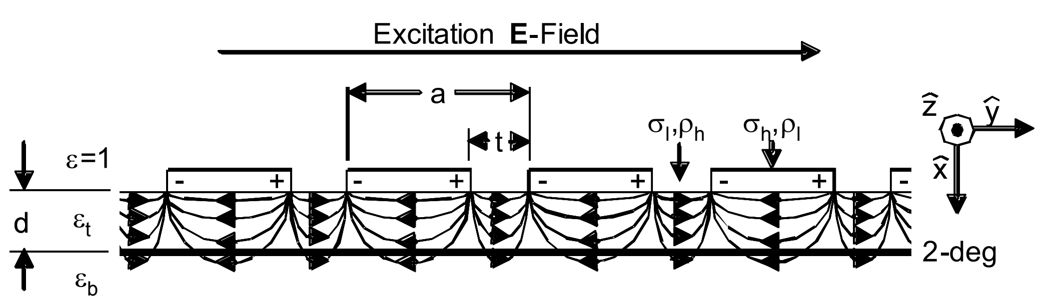

Figure 1. Incident THz field polarizes the grating, generating local fringing fields that excite plasmons in the 2deg.

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2. THEORY

The optical problem may be idealized to the interaction of local fringing fields near the grating and their influence on the 2DEG. The resonance frequency is determined by the plasmon wavevector and dispersion relation, given by[2,3]

$$\omega = \sqrt{\left(\frac{n_s e^2}{m^*}\right)\left(\frac{g_p}{\varepsilon_o\left(\varepsilon_b + \varepsilon_t Coth(g_p d)\right)}\right)} \quad (1)$$

where ε_t and ε_b are relative permittivities above and below the 2DEG, respectively, g_p is the plasmon wavevector defined by the grating period, and d is the distance from the grating to the 2DEG. In general, the plasmon wavevector can take discrete values of $2\pi p/a$, where a is the grating period and p is an integer. To obtain the highest fundamental plasmon frequencies, short grating periods, high sheet charge density, and a small effective mass are desirable. The derivation of this dispersion relation assumes that the gate region is entirely metalized, though with a large periodic modulation of the resistivity with period a. A different dispersion relation holds if there is no gate metallization at all, given by

$$\varpi^2 = \left(\frac{n_s e^2}{m^* \varepsilon_o}\right)\frac{g_p(\varepsilon_t Coth(g_p d)+1)}{\varepsilon_t(\varepsilon_b Coth(g_p d)+\varepsilon_t)+\varepsilon_t Coth(g_p d)+\varepsilon_b} \quad (2)$$

To calculate the transmittance spectrum, which reveals effects of temperature, grating geometry, and materials parameters, we use the theory of Zheng, Schaich, and MacDonald (ZSM),[3] which also yields the dispersion Equation (1). Equations used are given elsewhere[4] using the parameters indicated in Figure 1.

3. EXPERIMENT

Details of the fabrication of the devices in both InGaAs/InP and AlGaN/GaN materials systems are given in references [4] and [5,6], respectively. We highlight two significant differences between the two devices. For the InP device, a thin Ti layer (7.5 nm) was first evaporated over the entire patterned gate area, before the gate fingers were deposited by e-beam lithography. For the GaN device, there is no metallization between the gate fingers. The grating periods were 0.5 and 1.5 µm, and the depths of the 2DEG below the gate were 44.5 and 21 nm, for InP and GaN devices, respectively. Figure 2 shows the cross sectional diagrams for both devices.

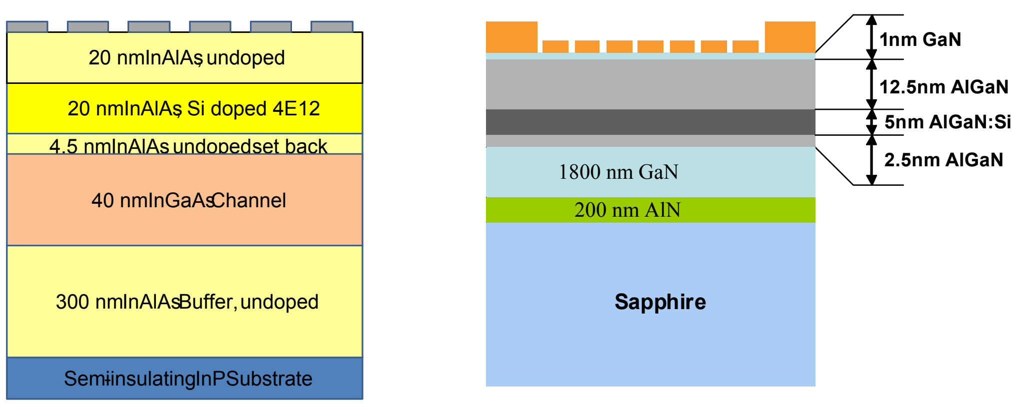

Figure 2. Epi-layer structure of InGaAs/InP and AlGaN/GaN devices. The 2DEG exists at the upper InAlAs/InGaAs interface and at the AlGaN/GaN interface in the left and right figures, respectively.

For transmission measurements, each device was mounted at the end of the light baffle within the helium cryostat of a 4 K silicon bolometer (IR labs). This was done to increase the collection efficiency of radiation transmitted through the small gate apertures. In the InP device, the gate aperture was smaller than all wavelengths, while for the GaN device the aperture was still only a few mm on a side. Since the device is not in direct contact with the 4 K cold plate, its temperature is somewhat elevated. We estimated in [4] that the actual device temperature was above 12 K. The opening to the bolometer is carefully screened so that all radiation reaching the bolometer must have passed through the gate region of both devices. The bolometer then records the modulated light from a Fourier spectrometer in the 10-100 cm^{-1} range using a 50 micron mylar pellicle beamsplitter and Hg arc lamp as a broad band source.

4. RESULTS

Measured (left), and calculated (right), transmission spectra for the InP and GaN devices are plotted in Figures 3 and 4, respectively. The measurements presented are undivided power spectra, revealing the overall shape of the beamsplitter modulation efficiency and any absorption present in the optics. Hence Figure 4 has a weak feature near 70 cm^{-1} that does not move with bias. This is likely due to the polyethylene cryostat window in this undivided spectrum. Absorptions due to the sample are those which shift with bias. Fast oscillations in both spectra are Fabry-Perot fringes caused by the substrate. For the InP sample, due to the small cross section of the sample, the throughput was very weak, the signature of the absorption resonance is the extinction of the Fabry-Perot oscillations.

The sheet charge density and relaxation time values used in the calculation for the InP device were determined from saturated current density measurements as described in [4]. In the GaN case, the actual values of n_s used in the calculation were those that gave the best fit to the measured spectrum. In Fig. 4 (right), additional 4th and 5th order resonances are also visible, which are not observed in the measured data. This is most likely due to the poor signal to noise ratio caused by the Fabry-Perot oscillations. It is worth noting here that third order peak is missing in the GaN device simulations. This is due to the impossibility of occurrence of third order term in the Fourier expansion of fringing fields when the grating has t/a ratio of ⅓.

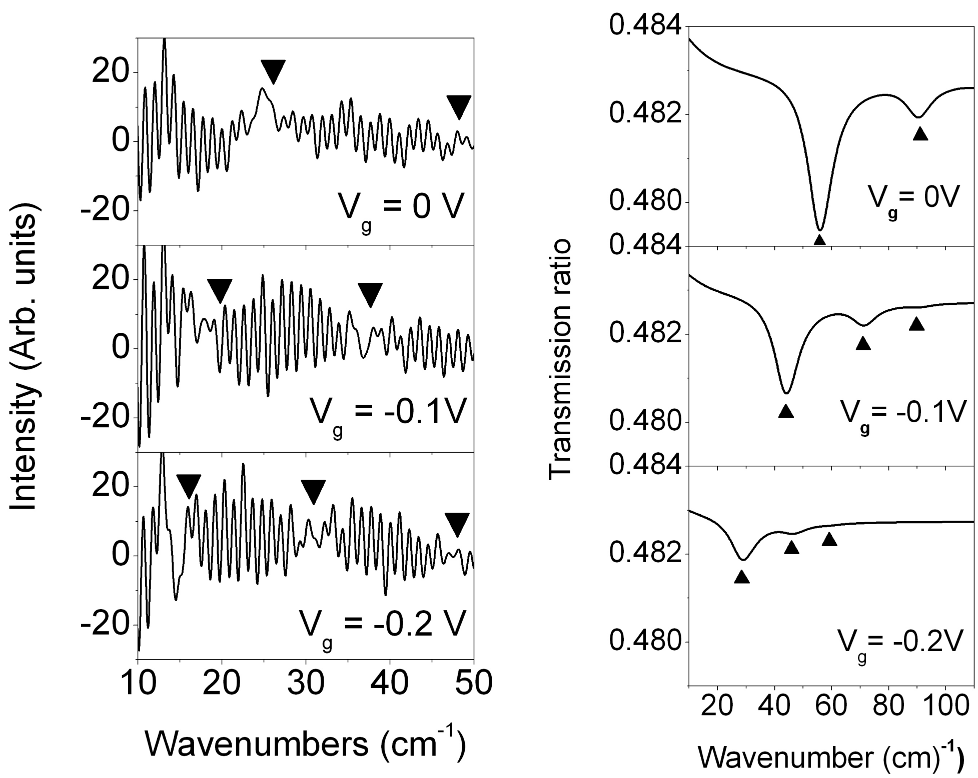

Figure 3. Measured and calculated plasmon absorption spectra for InGaAs/InP device.

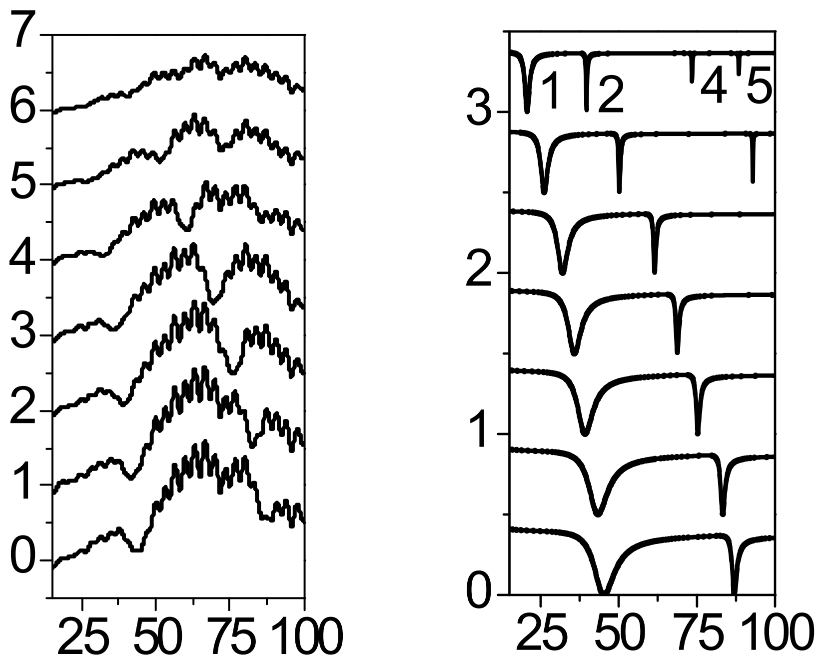

Figure 4. Measured and calculated plasmon absorption spectra for AlGaN/GaN device.

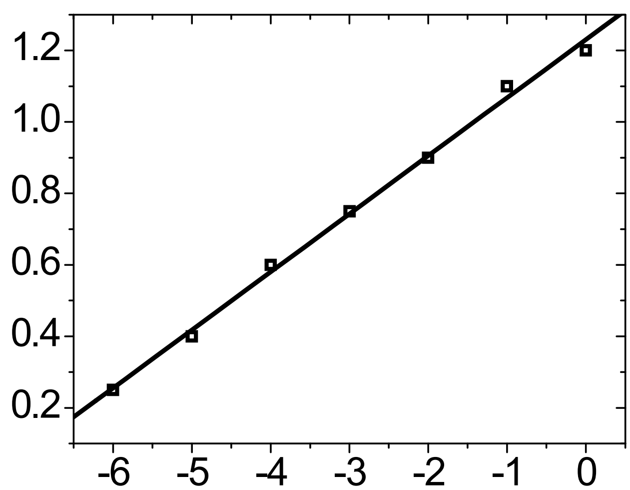

Figure 5. Best fit values of n_s for GaN device as a function of gate voltage together with linear fit.

5. DISCUSSION

The agreement of the GaN device results with the ZSM theory is excellent provided the sheet charge density is used as a fitting parameter to the dispersion relation of Equation (1). For the GaN device, the plasmon dispersion relation under the slits (ungated regions) does not change the overall dispersion too much because the plasmon velocity in the slits is very high compared to the gated regions. Plasmon propagation in the 2DEG is identical to multi-layered optical media with thick high-refractive-index layers and thin low-index layers (where indices are graded to match at the boundaries). If we suppose that the plasmon velocity in the ungated region is ~10× higher than under the gated region, then the plasmon remains only a small fraction of time in the ungated region. Thus, the gated region dominates the plasmon dispersion for the GaN device, since its ungated regions are very thin.

As stated, there is excellent agreement between theory and experiment for the GaN device provided n_s is determined from the resonance positions via curve fitting. By using Equation (1) to determine the sheet charge density as a function of gate bias, a sheet charge density versus gate voltage plot can be generated and is shown in Figure 5. The values are very reasonable in comparison to independent estimations of sheet charge density for this device as determined from the depletion threshold voltage measurements. The theoretical ratios of resonance frequencies are also in agreement with experimental ones, and such ratios are completely independent of n_s, according to Equation (1). In summary, the ZSM theory seems to work well for the GaN device, both in terms of absolute frequencies and in the ratios of harmonics, using values for sheet charge density obtained from the gated dispersion relation of Equation (1), which are also in good agreement with independent determinations.

The agreement for the InP device is is seen to be unsatisfactory, both in terms of absolute frequencies and their ratios, as already described in [4]. It is noted, that in this case, although the 2DEG sheet charge density was determined from IV characteristics as described in [4], simply using the sheet charge density as a fitting parameter, as was the case for the GaN device, still did not produce good agreement between experiment and the ZSM theory These discrepancies between theory and experiment are now discussed. Considering Equation 1, the ratios $\omega_p:\omega_1$ are seen to only be effected by the value of *d/a* and not by the value of n_s/m^*. Thus, by considering the resonant frequency ratios, as opposed to their absolute values, any experimental uncertainy in the 2DEG sheet charge can be negated. This *d/a* dependence is presented in Figure 6. Here it is observed that the ratios increase as root *p* for high values of *d/a* and as *p* for low values. The nominal *d/a* value is 0.089, giving frequency ratios 1.6 and 2.1 for p = 2 and 3, respectively. The observed ratios however are 2.0 ± 0.1 and 3.2, for p = 2 and 3, respectively. The uncertainty quoted is due to scatter when there is more than one data point. These observed ratios are significantly higher than the calculated ones, and they increase approximately as *p*.

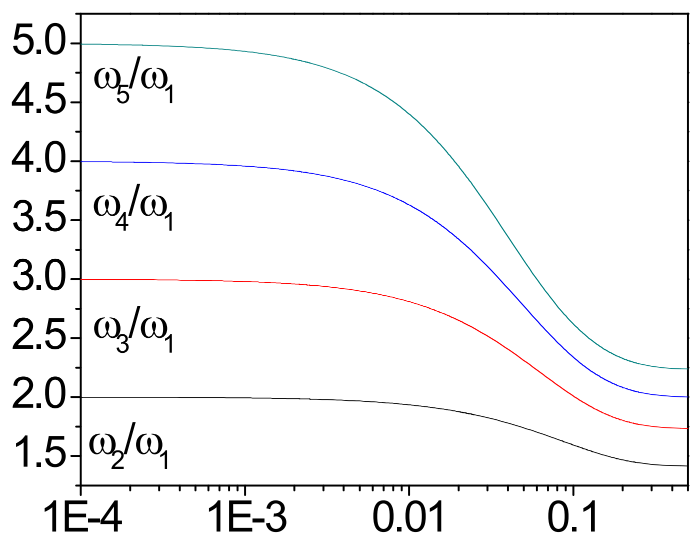

Figure 6. Ratio of higher plasmonic excitation harmonics to the fundamental as a function of the ratio of 2DEG depth (*d*) to grating period (*a*).

To speculate as to the probably cause of the discrepancy between ZSM theory and measurement for the InP device, we first consider the possibility of a significant ungated contribution to the dispersion, contrary to ZSM assumptions. In contrast to the GaN device, the InP device has 80% of the gate region with only very thin metallization and plasmons will remain for comparable time in both regions. ZSM theory supposes uniformity as pre-existing condition, which dictates a uniform dispersion law across the structure. But if the metallization is too thin in the gaps between grating fingers, the theory may be poorly suited for the InP device, since a contribution from a nearly-ungated region might be significant.

In the limit of zero Ti layer thickness, the actual dispersion relation for the device as a whole ought to be some kind of average between Equations (1) and (2). To illustrate what the effect of this might be, we consider the frequencies and ratios for a hypothetical entirely-ungated device, where the dispersion is that of Equation (2). Figures 7 and 8 present calculations in this case for the InP device. For any value of d or a, the calculated ratios are significantly smaller than any of the observed values. Fig. 8 shows only a weak dependence of the absolute frequencies on 2DEG depth d. The absolute frequencies might be explained by a larger value of a, such as the ~300 μm size of the gate aperture, but this does nothing to help the ratios. For nominal device parameter values, the absolute frequencies calculated based on Equation (2) are much larger than the measured frequencies.

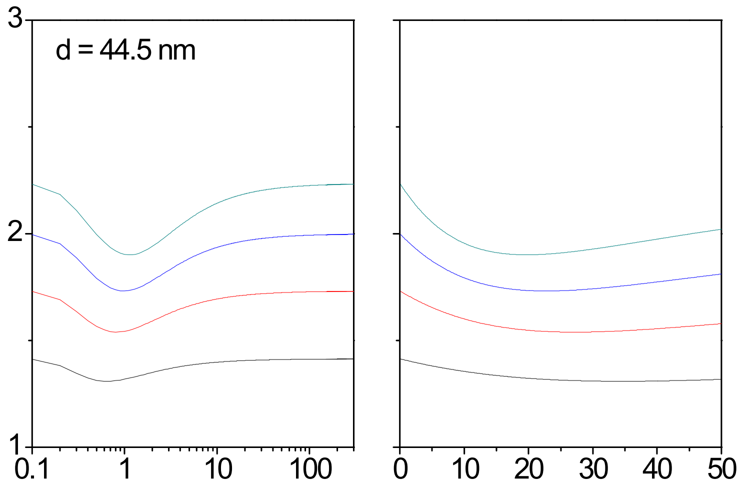

Figure 7. Calculated plasmon frequency ratios for the InP device as a function of 2DEG depth d and grating period a, based on ungated dispersion relation Equation (2).

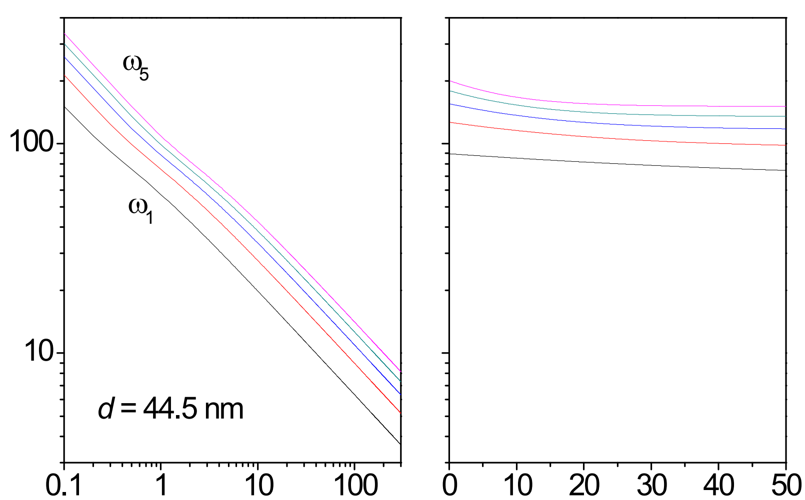

Figure 8. Variation of plasmon frequency for the fundamental and higher harmonics of the InP device as a function of gate period and 2DEG depth, based on the ungated dispersion relation Equation (2).

The plasma frequency in gated 2DEG channel is always less than in that in an ungated 2DEG since an image charge in the gate suppresses charge fluctuations. The frequency we measure is less than the lowest frequency possible for the nominal device parameters using either gated or ungated dispersion relations. Thus, supposing a significant contribution of ungated regions does not explain the InP device results.

Closer agreement between calculated and observed ratios for the InP device is achieved by supposing a smaller *d/a* value. Values of *d/a* that achieve this are below ~0.01. However, replacing *a* with any of the larger characteristic lengths in the device, such as the source to drain spacing as opposed to the grating period, wrecks havoc on the absolute frequency values. Though we believe that the gate/2DEG separation of 44.5 nm is accurate, based on selective etching and step profilometer measurements, an assumed smaller *d* value of 4.5 nm gives excellent agreement for both ratios and absolute frequencies, as indicated in Figure 9. This value of *d* is not the distance from the gate to the 2DEG, but coincidentally, it is the distance between the 2DEG and the Si-doped InAlAs layer.

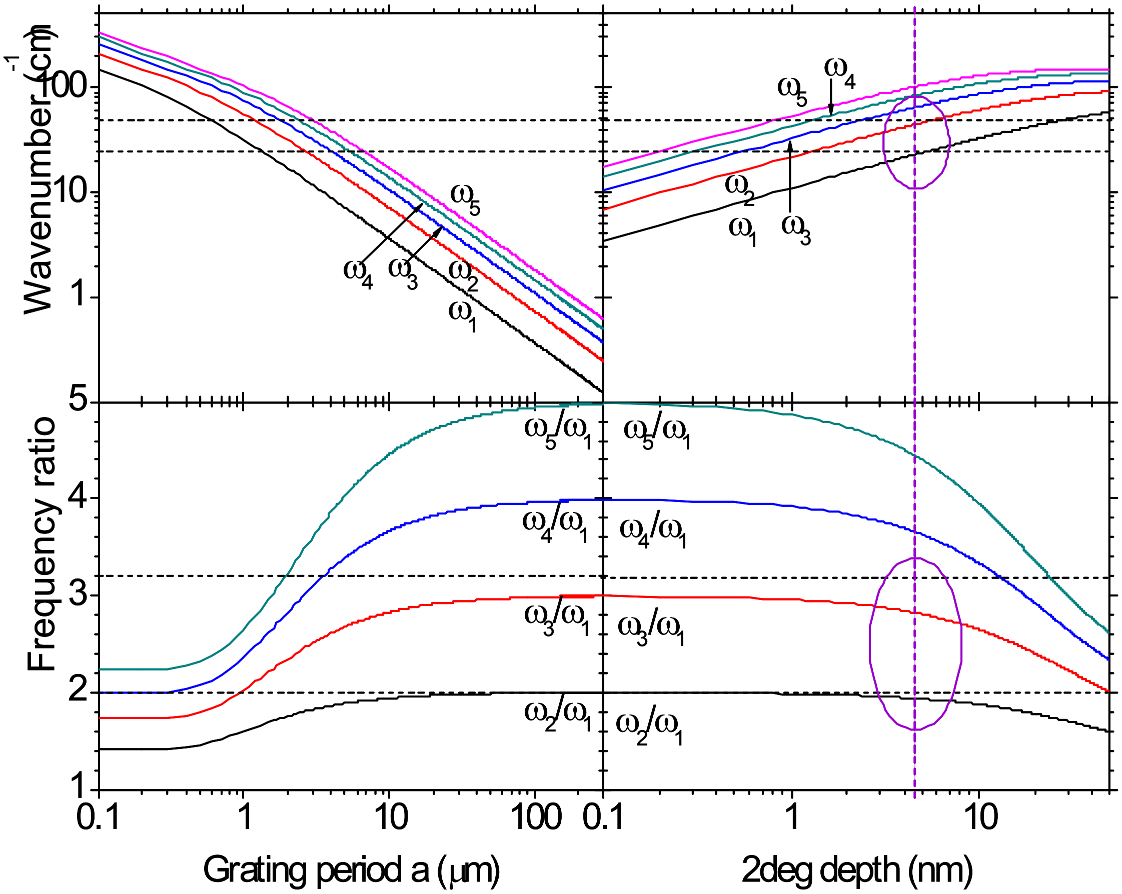

Figure 9. Calculated plasmon resonance frequencies and frequency ratios for the InP device. The left figures are for variations of grating period *a* assuming a 2DEG depth below the gate of *d* = 44.5 nm. The right figures are for variations in 2DEG depth *d* assuming a grating period of 0.5 μm. Horizontal dashed lines indicate experimental values. The vertical dashed line in the right figures indicates a *d* value of 4.5 nm, where theory and experiment are in reasonable agreement.

Assuming that the distance between the gate and the channel is ~4.5 nm results in satisfactory agreements with the results. It is suggested that an impurity band with significant conductance is associated with the heavily doped Si InAlAs layer. This layer may create a so called "virtual gate" 4.5 nm above the 2DEG. In this case the plasma excitations would have additional temperature dependent damping due to impurity band conductance, thus providing a means to test the assumption.

Based on this assumption of a "virtual gate", we derived a dispersion relation describing plasmon frequencies in the gated 2DEG in close proximity to a doped layer with finite dc conductivity such as provided by the doped InAlAs layer of this work. The conductivity, σ, of the delta layer is the fitting parameter of the theory. When σ approaches zero the dispersion relation reduces to Equation (1) where *d* equals the distance between the 2DEG and the gate (assuming continuous metallization with non-zero conductivity between the grating fingers). At large values of σ, dispersion equation reproduces Equation (1) with *d* equal to the distance between 2DEG and the doped layer. It also describes plasmon damping due to dissipation in the dopedlayer with finite σ. Work continues on fitting experimental data to this new dispersion relation in order to determine the σ curve fitting parameter. If this value is reasonable for impurity band conductance we will have strong reason to believe that we see plasmons screening due to conductance in the impurity band. Further, if we do observe a blue shift of the plasmon frequencies with decreasing temperature this would be very convincing, if not decisive, proof of this idea. This is because it is predicted that the impurity band conductance, σ, increases with increasing temperature.

6. ACKNOWLEDGMENTS

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