Tunable Terahertz Detectors Based On Plasmon Excitation In Two Dimensional Electron Gasses In Ingaas/Inp And Algan/Gan Hemt

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TUNABLE TERAHERTZ DETECTORS BASED ON PLASMON EXCIATION IN TWO DIMENSIONAL ELECTRON GASES IN InGaAs/InP and AlGaN/GaN HEMT

by

HIMANSHU SAXENA

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Physics
in the College of Sciences
at the University of Central Florida
Orlando, Florida

Fall Term
2009

Major Professor: Robert E. Peale
ABSTRACT

The observation of voltage-tunable plasmon resonances in the terahertz range in two dimensional electron gas (2-deg) of a high electron mobility transistor (HEMT) fabricated from the InGaAs/InP and AlGaN/GaN materials systems is reported. The devices were fabricated from a commercial HEMT wafer by depositing source and drain contacts using standard photolithography process and a semi-transparent gate contact that consisted of a 0.5 µm period transmission grating formed by electron-beam lithography. Narrow-band resonant absorption of THz radiation was observed in transmission in the frequency range 10–100 cm\(^{-1}\). The resonance frequency depends on the gate voltage-tuned sheet-charge density of the 2deg. The fundamental and higher resonant harmonics were observed to shift towards lower frequencies with the implementation of negative gate bias. The theory of interaction of sub millimeter waves with 2deg through corrugated structure on top has been applied to calculate and understand the phenomena of resonant plasmon excitations. The observed separation of resonance fundamental from its harmonics and their shift with gate bias follows theory, although the absolute frequencies are lower by about a factor of 2-3 in InGaAs/InP system. However, calculated values match much better with AlGaN/GaN system.
I would like to thank my advisor Dr. Robert E. Peale for giving me the opportunity to work in his research group at the Far Infrared Laboratory, Department of Physics. Without his motivation and constructive suggestions, this research would not have been possible. I would also like to thank Dr. Enrique Del Barco, Dr. Leonid Chernyak and Dr. Patrick L. LiKamWa for being on my dissertation committee and evaluating my thesis.

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CHAPTER ONE: INTRODUCTION

Terahertz (THz) are the electromagnetic radiation frequencies in the range of terahertz (10^{12} Hz). It occupies a place between the infrared and microwave regions in the spectrum. Traditionally, the THz spectral region was left unexploited for almost forty years. This is primarily owed to the lack of reliable bright sources in this part of spectra. This lack of suitable technologies led to the THz band being referred to as the “THz Gap”. The gap has rapidly dwindled in last two decades as a consequence of requirements from two very different research groups. On the smaller wavelength side, ultrafast time domain spectroscopists pushing towards longer wavelength and radio astronomers who, on the longer wavelength side, want to stride into smaller wavelengths. Frequency of 1 THz is equivalent to 4 meV in energy and thus THz band is teemed with myriad of spectral features with physical processes that share same order of energies. These processes include rotational and vibrational transitions of molecules and organic compounds, lattice vibrations in solids, intraband transitions in semiconductors and energy gaps in superconductors [1]. The THz band exhibits increasingly high absorption through atmosphere compared to its neighboring radio and infrared waves. The presence of water vapor is the prominent cause of THz attenuation in atmosphere. In addition, rotational lines of constituent molecules also occupy THz band that further dissipate the signal strength.

At 1 THz, liquid water has very high absorption coefficient [2] (≈250 cm^{-1}) because it has a strong polar molecule. Based on absorption strength at THz frequencies, condensed matter is classified in three broad categories, viz., water, metal and dielectrics. Metals are highly reflective (due to their high electrical conductivity). Non-polar materials such as paper, plastic, clothes,
woods and ceramics that are usually opaque at visible frequencies are transparent at THz frequencies. Table 1 summarizes optical properties of condensed matter in THz band region.

Table 1. Dielectric constants of selected solids at 1 THz, \( n_o \) stands for ordinary and \( n_e \) stands for extraordinary refractive index for birefringent materials.

<table>
<thead>
<tr>
<th>Solid</th>
<th>Refractive index</th>
<th>Power absorption</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire</td>
<td>( n_o = 3.070, n_e = 3.415 )</td>
<td>( \alpha \approx 1 \text{ cm}^{-1} )</td>
<td>3</td>
</tr>
<tr>
<td>Crystalline quartz</td>
<td>( n_o = 2.108, n_e = 2.156 )</td>
<td>( \alpha = 0.1 \text{ cm}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>Fused silica</td>
<td>( n = 1.952 )</td>
<td>( \alpha = 1.5 \text{ cm}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>Intrinsic-Ge</td>
<td>( n = 4.002 )</td>
<td>( \alpha = 0.5 \text{ cm}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>High-R GaAs</td>
<td>( n = 3.595 )</td>
<td>( \alpha = 0.1 \text{ cm}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>High-R Si</td>
<td>( n = 3.418 )</td>
<td>( \alpha &lt; 0.05 \text{ cm}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td>( n = 1.793 )</td>
<td>( \alpha = 8.6 \text{ cm}^{-1} )</td>
<td>4</td>
</tr>
<tr>
<td>0.19 ( \Omega )-cm N–GaAs</td>
<td>( n \approx 2.97 )</td>
<td>( \alpha = 320 \text{ cm}^{-1} )</td>
<td>5</td>
</tr>
<tr>
<td>0.36 ( \Omega )-cm P–GaAs</td>
<td>( n \approx 3.44 )</td>
<td>( \alpha = 270 \text{ cm}^{-1} )</td>
<td></td>
</tr>
</tbody>
</table>

These striking distinct features of THz band offer possibilities that are very explicit to this region of spectrum. Its ability to penetrate fabrics and plastics suggests that it can be used in imaging for the purpose of surveillance such as security screening for concealed weapons at airports [6-15]. Further, since most organic compounds (such as explosives, illicit drugs) have unique spectral “fingerprint” in this region the development of a standard and reliable identification is possible [16]. This provides an opportunity to develop spectral detection systems integrated to THz imaging that is immune to the influences from non-targeted materials. THz radiation can be used for medical imaging because it is non-ionizing nature and unlike X-rays.

does not damage DNA or tissues. Some frequencies of THz radiation can penetrate few millimeters of tissues with low water content (e.g. fatty tissues) [17]. THz radiation can also detect differences in water content in a tissue, which may allow the detection of certain type of cancer [18, 19].

The wavelength range from 1 mm to 100 μm corresponds to the photon energy of 1.2-12.4 meV. This is equivalent to blackbody temperature of 14 to 140 K. This is well below the surrounding temperature of earth. Results from NASA Cosmic Background Explorer (COBE) Diffused Infrared Background Experiment (DIRBE), and examinations of the spectral energy distributions in observable galaxies, indicate that approximately one-half of the total luminosity and 98% of the photons emitted since the Big Bang fall into the sub-millimeter and FIR [20, 21]. Much of this energy is being emitted by cooler interstellar dust at 10-20K. The dust forms interstellar medium in the Milky Way galaxy and distant starburst galaxies. There are several telescopes that are operating in this band. These are the James Clerk Maxwell Telescope [22], the Caltech Submillimeter Observatory and the Submillimeter Array at the Mauna Kea Observatory in Hawaii [23], the BLAST balloon borne telescope [24], the Heinrich Hertz Submillimeter Telescope at the Mount Graham International Observatory in Arizona [25] and Herschel Space Observatory [26].

**Diffraction of THz radiation by Grating**

In the far infrared (FIR) range, metal gratings can be modeled using the eigenmodes of a perfectly conducting grating. This is because the skin depth of a real metal for FIR is far less than the grating period. One of the most important uses of a grating in the FIR is to act as an optical coupler [27] allowing the nonradiative two dimensional plasmon resonances to interact
with freely propagating FIR radiation [28]. Mathematical treatment of the problem of diffraction of light by periodically corrugated structures started with Kirchoff’s scalar diffraction theory. Whichever of the field vector represent the electromagnetic disturbance, the disturbance is vectorial in nature. Since, the scalar theory ignores the vector nature of light it treats the interaction of light only in an approximate manner. Satisfactory results are obtained for diffraction problems are obtained where size of object is much larger than the wavelength of light. The approximation breaks down when size of the periodicity of the diffraction grating become comparable or smaller than wavelength (λ) of electromagnetic radiation [29]. The electromagnetic theory of gratings is being reviewed by Petit [30] who describes four classes of method that are applicable to a variety of grating diffraction problems.

The Rayleigh’s method: Following Kirchoff’s theory, an alternative approach to the diffraction problem was put forward by Lord Rayleigh [31]. This assumes that the total EM field above the perfectly conducting corrugated structure can be expressed as a Fourier series, where the Fourier coefficients are determined by applying the boundary conditions along the surface. This method yielded satisfactory results for shallow gratings even when the periodicity was smaller than λ. However, when the ratio of grating depth to periodicity exceeds a small critical value, the method fails to converge [32].

Modal-expansion methods: for certain grating profiles, it is possible to calculate a modal expansion of the fields in the grooved region. These expansions can then be matched to the Fourier components of the diffracted field outside the grating, giving an approximate solution if the series is terminated. Modal expansion may be used for lamellar gratings without the restriction to perfectly conducting metals or gratings with shallow grooves [33].
Integral methods: these methods rely on the fact that the diffracted fields can be expressed as integral of surface current density on the grating [34, 35]. The current is found by using the integral expressions for the field at the grating surface and applying the boundary conditions. This leads to an integral equation of the first kind, which can be solved approximately by various numerical techniques.

Differential methods: this method differs from the others in the way that it was originally developed for the case of dielectric and metallic gratings rather than the perfectly conducting case. The direct solution of the coupled partial differential equations that constitute Maxwell’s equations is possible but is very time consuming and is numerically stable for weakly modulated gratings.

**HEMT THz Detector**

A great deal of theoretical as well as experimental study of two dimensional electron gas (2deg) system has been done. The interaction of 2deg with FIR radiation has been an active area of research for almost last four decades [36-45]. The 2deg can be realized as a sharp increase in the magnitude of charge density confined within infinitesimal depth and in most of the cases lies in close proximity to the surface in Metal Oxide Semiconductor (MOS) structures. In such MOS structures, the sheet of charge where electrons are free only to move along the plane and restrained across the plane is induced by the formation of an inversion layer, which is brought in to effect by the onset of depletion region. The extent of depletion and therefore the sheet charge density $n_s$, is a function of gate voltage. The HEMT like MOS, also offers the realization of 2deg but unlike MOS, its construction naturally demonstrate superior charge transport characteristics.
**Plasmon excitations in 2deg**

Just like the surface of water where a disturbance would cause formation of ripples, any time variable electromagnetic field will induce density fluctuations in 2deg. The similarity exceeds mere spatial density fluctuations and like water waves that moves faster than water itself, plasmons have at least an order higher drift velocity. Thus the plasmons can be seen as a manifestation of ripples in the electronic fluid governed by the dispersion relation for plasmons in 2deg. These electronic ripples have well defined wavevector, which is a direct consequence of the periodicity of corrugated structure on top and is quantum mechanically connected to the momentum of such excitations.

These collective charge density excitations are quantized and are called plasmons. Plasmon excitation via optical means is hampered by momentum mismatch between the excitation field and subsequent plasmon oscillations. In order to transfer photon momentum to electrons there must be a finite in plane momentum component. Various methods have been developed to address this issue with one approach being common. A corrugated structure or grating is introduced between 2deg and freely propagating light to supply the required momentum in the integral multiple of $2\pi p/a$ where $a$ is the grating period and $p (= \pm 1, \pm 2\ldots)$ is an integer. For normal incidence, this is the acquired parallel wave vector. Thus for radiation at normal incidence to a properly designed grating both energy and momentum can be conserved in the excitation of fundamental ($p = \pm 1$) or higher harmonics ($p = \pm 2, \pm 3\ldots$) of plasmons with momentum $k_p = 2\pi p/a$. Since application of bias on gate results in the change of sheet charge density, grating can serve the dual purpose of transfer of momentum as well as the tuning of $n_e$. 

Plasma oscillations in a 2deg differ in a nontrivial way from the corresponding oscillations in 3D. The dispersion relation for such plasmon excitations is given by [46]

\[
\omega_p(k_p) = \sqrt{\frac{n_s q^2}{m^*_e \varepsilon_o (\varepsilon_b + \varepsilon_t \coth(k_p d))}},
\]

where \(\omega_p\) is the plasmon resonance frequency, \(n_s\) is 2deg sheet charge density, \(m^*_e\) is electron effective mass, \(q\) is the elementary charge, \(d\) is the depth of 2deg measured from gate, \(\varepsilon_o, \varepsilon_b,\) and \(\varepsilon_t\) are permittivity of free space, relative permittivity of material below and above 2deg respectively. To obtain the highest fundamental plasmon frequencies, short grating periods, high sheet charge density, and a small effective mass are desired. Once the device if fabricated, the grating period is fixed and thus the plasmon wave vector \(k_p\). Depth of the 2deg, permittivities and electron effective mass are also fixed once the heterostructures is designed. The only component that can be varied is sheet charge density, \(n_s\). This can be controlled by applying the gate bias. This gives such devices a very unique ability of tunability of resonances and thus making this a tunable THz detector.

**HEMT structure**

High Electron Mobility Transistor or HEMT is a field effect transistor that comprises of layers of different materials with different band gaps. As shown in figure 1, only an individual interface among multiple layers of a heterostructure provides 2deg. Due to the physical separation of 2deg from doped region, unlike MOSFET, HEMT is not susceptible to impurity scattering. Although being at the interface, it should still face the surface defect states such as dislocations or interface trap density due to stresses. The separation from uncompensated donor
ions is achieved by transporting high mobility electrons from a highly doped wide band gap n-type donor supply layer to an undoped low band gap narrow channel due to the formation of quantum well at the interface. The electrons that are transported from the n-type doped layer promptly fell and get trapped in to the quantum well formed at the junction of interface of two layers. This interface accommodates the 2deg and forms the channel. Since the electrons have fallen in to the quantum well with discontinuity in the conduction band of undoped low band gap layer, availability of large number of states as well as absence of impurities results in a very large mobility. Such heterostructures can be fabricated with very high precision and controlled manner using molecular beam epitaxy (MBE) technique.

![Figure 1. Schematics of grating-gated HEMT and formation of potential well at the interface of two different bandgap layers.](image-url)
CHAPTER TWO: THEORETICAL BACKGROUND

To determine the features of the Plasmon resonance spectra in more detail, the theory of plasmons in grating-coupled 2deg devices is used here [50]. The theoretical approach to the problem is to analyze and evaluate the effect of grating coupler. The confined electron system is considered to be homogenous, two-dimensional, electron gas where electrons are free to move along the sheet of charge. Electrical response of 2deg is characterized by the sheet charge density $n_s$, electron effective mass $m^*$ and a Drude relaxation time $\tau$.

Let $z$ be the direction of metal stripes of grating and $y$ the orthogonal direction in the grating plane. Since the metal stripes are oriented along $z$, for the sake of theoretical point of view, they may be consider to be infinitely long along $z$ and thin along $y$. This is reflected in their conductivity, which is infinitely high along $z$ and zero along $y$. This makes the isolated grating a linear polarizer.

The THz radiation incidents along the normal to the grating plane. The physical thickness of such a grating is much smaller than its separation form underlying confined electron system $d$. The optical problem may be idealized to be the coupled response of a pair of two-dimensional layers. Further, since the grating period, $a$, is considerably smaller than the wavelength of incident radiation, waves cannot propagate away. Thus all the diffracted beams are evanescent waves. Referring to figure 2, spatially uniform THz electric fields polarize the grating bars, which induces local fringing fields with the grating periodicity. The theory explains the excitation of plasmons via these fringing fields and the consequences of such excitations on transmission of zeroth-order-diffracted beam through subwavelength openings in the grating.
For an unpolarized beam that incidents along surface normal to the grating plane, the coefficient of transmission is given by,

\[ T = \frac{1}{2}(T_y + T_z), \]  

(2.1)

where \( T_y \) and \( T_z \) are the transmission coefficients for \( y \)- and \( z \)-polarized radiation respectively. \( T_y \) in zero magnetic field and in Gaussian units is

\[ T_y = (e_y)^{1/2} \left[ \frac{2}{1 + (e_y)^{1/2} + \frac{4\pi}{c} \sigma_y} \right]^2, \]  

(2.2)

and \( T_z \) is obtained by substituting \( z \) for the \( y \) subscript. The complex \( yy \)-component of the conductivity tensor is

\[ \Sigma_{yy} = \sigma(\omega) + \sigma_{yy}^g, \]  

(2.3)

while the \( zz \)-component is given by

\[ \Sigma_{zz} = \sigma(\omega) + \langle \sigma_{zz}^g \rangle, \]  

(2.4)

where \( \langle \rangle \) indicates a spatial average, and \( \sigma(\omega) \) is the conductivity associated with the 2-deg only.

The second terms are components of the grating conductivity tensor. Only \( \sigma_{yy}^g \) interacts with the 2deg. The \( \langle \sigma_{zz}^g \rangle \) is independent of the 2deg due to the lack of fringing field components polarized in the \( z \)-direction. All off-diagonal components of \( \Sigma \) vanish in the absence of a magnetic field.
The second terms are components of the grating conductivity tensor. Only $\sigma_{yy}$ interacts with the 2deg. The $\langle \sigma_{zz} \rangle$ is independent of the 2deg due to the lack of fringing field components polarized in the $z$-direction. All off-diagonal components of $\Sigma$ vanish in the absence of a magnetic field.

The frequency dependent conductivity of the 2-deg is

$$\sigma(\omega) = \frac{n, q^2 \tau}{m^* (1 + \omega^2 \tau^2)},$$

(2.5)

where $\tau (= \frac{m^* \mu}{q})$ is the electron relaxation time and $\mu$ is the temperature-dependent electron mobility. The last term of Eq. (2.3) is treated in the perturbative approximation according to

$$\sigma_{yy}^e = \frac{1}{\langle \rho \rangle} - \sum_{m>0} \left( \frac{\tilde{\rho}(m)}{\langle \rho \rangle} \right)^2 \frac{F_m}{2},$$

(2.6)
where \( \langle \rho \rangle \) is the spatially averaged 2D resistivity of the grating, \( \bar{\rho}(m) \) is the \( m^{th} \) Fourier coefficient in the cosine expansion of the \( yy \)-component for the grating resistivity tensor given by

\[
\bar{\rho}(m) = \frac{2}{\pi m} (\rho_h - \rho) \sin \frac{\pi m}{a},
\]

and

\[
F_m = (i\omega/4\pi G_m) \left[ 1 + \varepsilon_i \text{Coth}(G_m d) + \frac{\varepsilon_i^2 (1 - \text{Coth}^2(G_m d))}{4\pi G_m \sigma(\omega) + \varepsilon_h + \varepsilon_i \text{Coth}(G_m d)} \right],
\]

Following Ref. 24, the sum Eq. (2.6) is truncated after \( m = 10 \).

\[
\langle \sigma \rangle = \frac{t}{a} \sigma_i + \left( 1 - \frac{t}{a} \right) \sigma_h,
\]

and

\[
\langle \rho \rangle = \frac{t}{a} \rho_h + \left( 1 - \frac{t}{a} \right) \rho_i.
\]

**Example Calculations**

For the figure 8 based as-grown MBE epi-layer structure of InGaAs/InP, electron relaxation times of \( \tau = 0.25 \) (0.65) ps were measured at 300 (77) K. As will be shown below, these values are insufficiently high to produce sharp plasmon resonances, but they can be increased by cooling the device. Figure 3 plots \( \tau vs T \), where the measured data points appear as symbols. Symbols represent values calculated from the measured mobility. The \( T^{-3/2} \) curve (heavy line) is a least squares fit to the data and was used for all simulations, although the \( T^{-0.7} \) curve (light line) represents a better fit to the limited data. Assuming that phonon scattering dominates the carrier relaxation, the temperature dependence should obey a power law with a
\( \frac{3}{2} \) exponent, [51] which we use to estimate the low temperature \( \tau \) values even though the actual data fall on a curve with an exponent closer to -0.70 (light line).

![Figure 3. Temperature dependence of the relaxation times for the 2-deg.](image)

Based on the theory and design presented above, transmission spectra were calculated, assuming a grating period \( a = 0.5 \, \text{\textmu m} \) and a 2-deg depth \( d = 37 \, \text{nm} \). Figure 4 illustrates the effects of sheet charge and effective mass uncertainty at 4 K, where the sheet charge density of \( 2.4 \times 10^{12} \, \text{cm}^{-2} \) is varied by a factor of two, while the effective mass of 0.043 is increased by 50% to 0.065 [52]. With these changes in material parameters no change is seen in the plasmon FWHM of \( \sim 1.7 \, \text{cm}^{-1} \). Changing the effective mass by 50% however causes a 19% decrease in the peak position wave number. Changing only the sheet change by a factor of two causes a 29% decrease in the peak position wave number. Uncertainty in peak position of this magnitude were not supposed to affect our planned experiment with the p-Ge laser, whose full tuning range is 50-140 cm\(^{-1}\). It is noted, that although the peak position accompanying these material changes could be determined by the much simpler Eq. (1), the more detailed theory of Ref [50] was still required to determine the overall plasmon line shape.
Figure 4. Simulated transmittance for the device of this work showing effects of changes to effective mass and 2-deg sheet charge density.

Resonance line width and absorption strength depend on temperature as shown in Figure 5 (a) and (b). Figure 5 (a) shows typical 1\textsuperscript{st} order transmittance spectra for $n_s = 2.4 \times 10^{12}$ cm\textsuperscript{-2} and $t/a = 0.65$. The temperature dependence of metallization resistivity is ignored because resistivity changes in the semi-transparent gate affect mainly the baseline transmittance. Moreover, residual resistance for thin semitransparent Ti films can be so high that the temperature dependence is weak [53]. Thick Au grating bars are opaque and the decrease in their resistivity with cooling has no effect on the spectrum at all. Fig. 5 (a) shows that there is still a small but measurable signal even at a temperature of 100 K. Figure 5 (b) plots both the percentage change of the transmittance as well as the simulated full width half maximum (FWHM) of the resonance peak for both 1\textsuperscript{st} and 2\textsuperscript{nd} order resonances. It is clear from this plot that the 2\textsuperscript{nd} order peaks are not as deep and are slightly narrower in line width at lower temperatures.
Figure 5. Simulation of reduction in transmission through the device of this work at resonant condition as a function of temperature. (b) Details of similar calculations for both first and second order plasmon resonances.

Figure 6 presents the transmission plotted as a function of t/a ratio for both the 1st and 2nd order resonances. Figure 6 (a) shows similar peak heights for all t/a ratios with a slight narrowing of the peak as the t/a ratio is increased. Figure 6 (b) shows a rapid reduction in peak height as the t/a approaches the symmetric case of t/a = 0.5. This is caused by the impossibility of even-order terms occurring in the Fourier expansion of the fringing fields when the grating is symmetric.
Figure 6. Calculated effect of changing grating duty t/a on (a) first order and second order plasmon induced transmission spectrum.

Figure 7 illustrates the calculated voltage tunability where device transmittance is plotted at various gate biases. For this and all subsequent figures a t/a ratio of 0.65 and a zero bias 2-deg sheet charge of $2.4 \times 10^{12}$ cm$^{-2}$ were used. As can be seen, a voltage swing of 0.55 volts allows for detection of incident radiation from roughly 2.75 THz to 3.75 THz. In principle, increasing the grating period can shift this 1 THz detection band for the given semiconductor layer structure to any desired lower frequency.
Figure 7. Resonance tuning with gate voltage.
CHAPTER THREE: EXPERIMENTS

HEMT Device Design

Two distinct systems of heterostructures were chosen for the observation of plasmon excitations and the tunability of such excitations. Both systems constituted the three terminal HEMT devices. The following section will describe them separately.

InGaAs/InP system

The MBE grown epitaxial layer structure for the device of this work is shown in figure 8 along with the physical layout of a single device in figure 9. The 100 mm diameter wafer is a commercial HEMT wafer material purchased from International Quantum Epitaxial (IQE). 25 nm capping layer is removed before gate metallization using a 27:1 selective etch. This put 2deg at the In$_{0.52}$Al$_{0.48}$As/In$_{0.53}$Ga$_{0.47}$As interface, at the depth of 44.5 nm beneath the gate. The layout of this HEMT is that of a typical device with a few notable exceptions. In order to maximize the detection of any plasmon resonance, the gate length and width are 195 and 250 µm respectively. This, however, is achieved at the expense of device switching speed. Also the entire 3.5×3.5 mm$^2$ die is designed such that any incident radiation can only pass through the gated area. A multi level metallization has been undertaken to accomplish this. An inter-level dielectric of B-staged Bisbenzocyclobutene-based polymer (BCB) was used throughout the fabrication process so that all metal layers could overlap each other in order to minimize light transmission and still maintain electrical insulation. This was carefully designed with a clear intention of masking the
detector kept behind the mount everywhere except the gate. With this setup, any change in device transconductance can be directly correlated with reduced transmission through the device, a signature of plasmon resonance.

![Figure 8. Epi-layer structure schematic of voltage tunable plasmon based detector.](image)

Fabrication was undertaken using standard optical contact lithography and a combination of wet chemical etching for the semiconductor and dry etching for the BCB dielectric. No BCB was left over the gate opening in order to maximize the optical throughput. After removal of the InGaAs capping layer in the gate region, the gate/grating was formed in two steps. A thin (75 Å) film of Ti (with a sheet resistance assumed for calculation purposes to be $\rho_n \sim 350 \Omega/sq.$) was first evaporated over the entire patterned gate area. The thickness was chosen such that the incident radiation would not be substantially blocked and it was made continuous in order to achieve the most uniform gate control over the 2deg sheet charge density. On top of this Au grating stripes were deposited (with a sheet resistance assumed for calculations to be $\rho_l \sim 0.14 \Omega/sq.$). The gate/grating was then fabricated using e-beam lithography. After spin
coating with positive tone PMMA, 30 keV electron beam was used to pattern the 0.25 µm grating stripes with a period of 0.5 µm. A metal stack of 150Å/1000Å Ti/Au was then evaporated and lifted completing the fabrication of gate/grating. As seen in the scanning electron micrograph of the device in figure 10, there appears to be slight noise problem associated with the sub-micron e-beam patterning. Owing to its small size compared to the wavelength these small jittering would not substantially affect the device performance.

Figure 9. Physical layout of device.
Eq. (1) determines the high frequency limit of the structure. Required material parameters, as shown in figure 8 (heterostructure) are found as follows. The permittivity of semiconductor alloy $A_{1-x}B_x$ is determined from the permittivities $\varepsilon_A$, $\varepsilon_B$ of the end members A, B according to

$$\varepsilon_{AB} = (1-x)\varepsilon_A + x\varepsilon_B - x(1-x),$$

for both InGaAs and InAlAs [47]. Using $\varepsilon_{AlAs}=10.2$, $\varepsilon_{InAs}=14.6$, and $\varepsilon_{GaAs}=13.1$, we obtain $\varepsilon_I=12.24$ for the In$_{0.52}$Al$_{0.48}$As layer above the 2-deg and $\varepsilon_0=13.65$ for the In$_{0.53}$Ga$_{0.47}$As below the 2-deg. Using an effective mass of 0.043 for electrons in the InGaAs channel [48], we obtain from eq. (1) a plot of excitation frequency versus sheet charge density and grating period. From figure 11, a grating period of 0.1 µm and a sheet charge density of $3 \times 10^{12}$ cm$^{-2}$ provide a minimum detectible wavelength of 26 µm.
To determine the effects of gate bias, the 2-deg sheet charge density, $n_s$, is given by

$$n_s = C_{\text{gate}} \frac{(V_g - V_t)}{qLW},$$  \hspace{1cm} (3.2)

where $V_g$ is the gate bias, $V_t$ is the device threshold voltage, $L$ is the gate source to drain spacing, $W$ is the gate width and $C_{\text{gate}}$ is the gate capacitance. The latter can be approximated (in S.I. units) by

$$C_{\text{gate}} = \frac{\varepsilon_r\varepsilon_0 LW}{d},$$  \hspace{1cm} (3.3)

where $n_d$ is the delta doping concentration of the heterostructure and $E_c$ is the conduction band offset. For the InGaAs/InAlAs system, when the In mole fraction in In$_x$Ga$_{1-x}$As exceeds 58%, $E_c$ is given by [49]

$$E_c = 0.344 + 0.487x$$  \hspace{1cm} (3.4)
For an MBE grown epi-layer structure of figure 8 design, Hall measurements indicate a sheet charge density of $2.4 \times 10^{12}$ cm$^{-2}$ and a mobility of 10100 (26500) cm$^2$/V-s at 300 (77) K. Using a typical barrier height for metal on a III-V compound of $\phi_b = 0.7$ eV and all other values as previously defined, a linear decrease in sheet charge is expected with a maximum value at $V_g=0$ and zero at $V_g=-1.3$ V.

**AlGaN/GaN system**

The AlGaN/GaN HEMT structures used in this study were grown by migration enhanced metal-organic chemical vapor deposition (MEMOCVD) on sapphire substrate. Top layer consisted of 100 nm thick AlN buffer followed by 1.4 µm thick undoped GaN layer. Al$_{0.2}$Ga$_{0.8}$N barrier layer was doped with silicon to approximately $2 \times 10^{18}$ cm$^{-3}$. 2deg electron concentration has been measured to be $10^{13}$ cm$^{-2}$ at room temperature. Metal grating gates with periods $a$ from 1.5 to 3.5 µm were evaporated on top of the structure. The barrier layer (Al$_{0.2}$Ga$_{0.8}$N) between metal grating and 2deg was 21 nm. Gap between gate fingers for periods 1.5 and 3.5 µm was 0.5 µm so that the width of grating fingers were 1 and 3 µm, respectively. Ohmic contacts and gates were fabricated using e-beam evaporation of metal stack of Ni/Al/Ni/Au and Ni/Au. The grating fingers were designed in such a way that every consecutive finger comes from the opposite side and both sides of the gratings were shorted. Active region of the device was approximately $2.5 \times 2.5$ mm$^2$ covered by the periodic grating structure. Such large active area of the devices made them suitable for higher signal throughput and study by the conventional FTIR technique.

There were two types of measurements proposed. The one that involved the measurement of transmission of THz field accompanying resonant plasmon excitation signature and two, photoconductive measurements aimed at measuring changes in conductivity at the onset of
plasmon resonance. Experiment setup was carefully designed to obtain both sets of measurements simultaneously.

**FTIR Measurements**

The approach that we could implement were to be free of any external EM noise as explained in the section (that discusses $p$-type Ge experiments) following FEL experiments. The obvious choice was Bomem D8 FT Spectrometer. The sample/device was still to be cooled to L-He temperature to get rid of phonons as they share the similar energy range as THz radiation. A new mount specially designed to couple device with bolometer. The whole assembly was attached to the Bolometer light baffle. Care was taken not to allow any or minimize radiation leak from the edges. The platform provided electrical connection pads as well as impeded any stray radiation that might enter into the bolometer. Instead of top of 4K plate, the device was sitting on top of printed circuit board platform. Thermally and electrically isolated, its temperature was somewhat elevated. The whole assembly, i.e., sample/device and bolometer were then coupled with Bomem spectrometer for transmission measurements.

**FEL Experiments**

The UCSB mm-wave free electron laser (FEL) was used to search for resonant photo-response in the device, which was mounted in a temperature-controlled closed-cycle cooler. The FEL pulse repetition rate was $\sim 1$ Hz and pulse duration $\sim 1$ $\mu$s. Pulse energy was measured and recorded for every laser shot. The polarization was horizontal but could be rotated to vertical using wire-grid polarizers. The device was oriented so that the grating stripes were vertical. Crossed polarizers were used to determine the FEL power dependence of the observed photo-
response. The gate was biased using a battery and potentiometer in the range -0.5 to 0.3 V. Two different schemes were used to apply the source-drain bias. The first biasing scheme, shown in Figure 12 (a), used a current supply to provide constant source-drain current $I_{SD}$ through the device with the drain grounded, while the voltage across the device $V_{SD}$ was monitored on an AC coupled oscilloscope as a function of gate bias $V_{GD}$. In the second scheme, figure 12(b), the HEMT was biased with a constant 0.25 mV at the source and a load resistor, $R_L$, of 10 kΩ from drain to ground. The voltage drop, $V_L$, across the load was monitored on an oscilloscope synchronous with the FEL pulses. As expected, the steady state dark value of $V_{SD} (= 0.25\text{mV} – V_L)$, does change as the gate voltage sweeps, indicating proper gate control. However, because of the small source bias condition, the change in $V_{SD}$ from $V_G = 0$ to pinch-off remains less than 10 mV. Data with a small $R_L$ (100 Ω) and with large $V_S = 0.5$ V was also collected. In addition, a shunt capacitor of $C = 100$ nF connected from source to ground was experimented with in order make the circuit time constant longer relative to the FEL pulse width. This assures that the power supply can be adequately adjusted to fix the voltage on the time scale defined by $R_L C$. As expected, with the shunt capacitor, there was less noise.
Figure 12. Constant current scheme used for device biasing in this work. And (b), constant voltage scheme.

Transmission measurement using $p$-type Ge laser

An insert has especially been designed keeping in mind the mounting of a device, provision of electrical contact with external measurement devices and shielding of electromagnetic interference. The insert consists of brass platform providing mounting stages for both devices on PCB and Ge detector beneath the PCB. On top, it is fitted with hermetically sealed connector to inhibit entrance of air and moisture and provide good insulation from interference.

Primary objective of this experiment involved measurement of transmission coefficient of THz radiation. An external gate bias could tune the device, which is a field effect transistor (FET), for the detection of given range of THz frequency. Such an experiment must be performed at liquid He temperature as shown in Figure 13. A specially designed insert had been prepared that would contain device, a Ge-detector that sits beneath the device, and provides an access to external measurement units.
Care has been taken to avoid any vent or possibility for air inlet to prevent the formation of ice. This is very important as water has a strong absorption coefficient starting from 10 μm to mm waves. Another important issue in the design of experiment is shielding device and Ge detector from strong electro-magnetic (EM) interference that originates from strong pulsed electric field around p-type Ge crystal. Since device and Ge detector sit so close to the laser, addressing the EM shielding is an important issue. A hermatically sealed connector (Amphenol PT-SE Connector (M) and Amphenol MS3116 Cable Mount Straight Plug (F)) is installed on top of insert. Figure 13 also shows the schematic diagram of insert. A double level brass platform is machined for mounting Ge-detector beneath device. This is surrounded by another thick brass pipe that would prevent any leakage of external EM interference that may reach device and modify the device behavior.

![Figure 13. Schematics of transmission and photoconductivity experiment.](image)

Figure 14 represents the schematics for the PCB mount designed for holding the device. Both sides of the PCB mount are Cu coated to prevent leakage of THz radiation. Three holes on
the periphery provide electrical access to the device. The holes were filled with solder to block any possible opening for THz radiation. The central hole that coincides with grating/gate provides passage for THz radiation and Ge detector sits beneath this hole.

![Diagram of PCB mount for device](image)

**Figure 14. Schematics of PCB mount for device (all units are in inches).**

Planned experiment for the InP device involved a powerful semiconductor laser which is unique to our lab. Based on p-type Ge, it operates in the wavelength range of 70-200 μm (1.5 to 4.2 THz). Thus, p-type Ge laser is our natural choice source that we intend to use for plasmon excitation. A typical output spectra of p-type Ge laser operating on total internal reflection modes and without a wavelength selection is shown in figure 15. The total peak power emitted is ~50 Watts [54]. Initial approach of measurement of plasmon resonance consisted of using a high-power THz p-Ge laser at liquid helium temperatures. A multimode output spectrum presented in figure 13 demonstrates its suitable bandwidth and a range of features that can be recorded as the device resonance tunes with gate bias. The device is mounted in the He dewar between the p-Ge laser and a Ge:Ga photodetector as shown in figure 13. Electrical leads connecting source, drain and the gate/grating are then used to vary the sheet charge density while
monitoring the device transconductance. Transmission through the device can be simultaneously monitored with the 4 K Ge:Ga photoconductor. Based on the spectrum for the p-Ge laser and the maximum measured sheet charge of the epilayers, a grating period of 0.5 µm has been chosen to allow tunable detection across the entire output bandwidth of the laser with gate voltages from 0 V to -0.6 V.

Figure 15. Typical output spectra of p-Ge laser.
CHAPTER FOUR: RESULTS AND DISCUSSION

As mentioned in chapter three, two sets of measurements were performed. The experiments were aimed at the measurement of transmission spectra in a given bandwidth where resonant plasmon excitations are located and the observation of any measurable changes in the 2deg conductivity at the onset of a plasmon resonant excitation.

InGaAs/InP device

Measured IV curves are presented in figures 16 and 17. The inset of figure 16 presents a schematic of how the device was wired for the IV measurements. Gate voltages $V_g$ and source voltage $V_s$ are referenced to the drain, which is grounded. Figure 16 presents a family of transfer curves ($I_{sd}$ vs $V_g$) indicating proper gate control. At room temperature, $I_{sd}$ is pinched off at about $V_g = -400$ mV, while at 22 K this occurs around -200 mV. Figure 16 presents a family of $I_{sd}$ vs. $V_s$ curves at room temperature and at 22 K for $V_g$ in the range 0 to -0.4 V. At $V_s$ values in the range 100-200 mV, $I_{sd}$ saturates.
Figure 16. Transfer curves. $I_{sd}$ as a function of $V_g$ at various source biases. The inset is a wiring diagram for IV measurements. For each temperature, data was acquired at $V_s = 0.1$ (lower curve) and $0.3$ V (upper curve).

Figure 17. Source-drain current as a function of source-drain bias at various gate voltages and for two different temperatures.

Figure 18 presents the saturation current vs. $V_g$ for three temperatures. Here the decreasing $V_g$ required for pinch-off as temperature is decreased is evident. Fits of Eqs. (1-4) to
the data are also plotted, and the fitting parameters $\mu$ and $n_d$ are tabulated in the inset for the three temperatures. In these fits, the In mole fraction $x = 0.532$, $v_s = 1.6 \times 10^5$ m/s, $\varepsilon_i = 12.24$, and $\varepsilon_b = 13.65$. (Permittivities were calculated from Eq. 5 using $\varepsilon_{\text{AlAs}} = 10.2$, $\varepsilon_{\text{InAs}} = 14.6$, and $\varepsilon_{\text{GaAs}} = 13.1$). An effective mass $m^* = 0.043$ is taken for the electrons in the InGaAs channel, although the actual value may be as much as 50% higher due to wave-function bleeding into the InAlAs barrier material. We note that the room temperature zero bias value of mobility, $\mu = 7250$ cm$^2$/V-s is smaller than both our own Hall value of 11331 cm$^2$/V-s and that specified by the manufacture of 10100 cm$^2$/V-s. Saturation current and Hall measurements are performed for very different biasing conditions, which can easily explain the difference. The $n_d$ value of $9.3 \times 10^{11}$ cm$^{-2}$ is ~4x less than the nominal delta-doping level value of $4 \times 10^{12}$ cm$^{-2}$.

From the mobility values, relaxation times 0.18, 0.44, and 0.60 ps at 300, 22, and 12 K are found, respectively. They do not follow the $T^{-3/2}$ dependence [51] one expects from temperature dependent phonon scattering, suggesting that temperature-independent impurity, alloy, or interface scattering are important. Thus, the plasmon resonance line width is not expected to decrease continuously with decreasing temperature.

Figure 19 presents plasmon resonance frequency values calculated from Eq. (6) using $a = 0.5$ $\mu$m. The $p$ values indicate fundamental and harmonics. The $n_s$ values at zero gate bias determined from Eqs. (3, 4) using $n_d$ values from Fig. 17 are indicated by symbols in figure 18 for three temperatures. These results indicate a fundamental frequency of 56.3 cm$^{-1}$ at 22 K and $V_g = 0$. Our room temperature Hall data indicate a sheet charge density of $1.17 \times 10^{12}$ cm$^{-2}$, which is 40% higher than the $6.7 \times 10^{11}$ cm$^{-2}$ value obtained from the $I_{\text{sat}}$ curve fitting. For the $I_{\text{SDsat}}$ measurements, the added gate contact might slightly increase the surface depletion.
Figure 18. Curve fits of saturation current as a function of gate bias at various temperatures. The fit parameters $\mu$ and $n_d$ are tabulated in the inset.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>$\mu$ (cm$^2$/V-s)</th>
<th>$n_d$ ($10^{11}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>7250</td>
<td>9.33</td>
</tr>
<tr>
<td>22</td>
<td>17800</td>
<td>7.3</td>
</tr>
<tr>
<td>12</td>
<td>24600</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Figure 19. Calculated plasmon resonance wavenumbers as function of sheet charge density. The symbols on the abscissa indicate values of $n_s$ for $V_g = 0$ determined from experimental IV curves at the three temperatures indicated.

Figure 20 presents transmission spectra calculated for $T = 22$ K, where $n_s$ values are 4.6, 3.0, and $1.5 \times 10^{11}$ cm$^{-2}$ at $V_g = 0$, -0.1, and -0.2 V, respectively. A grating duty cycle $t/a = 0.8$ was taken according to figure 2. All spectra presented in figure 19 have been divided by calculated
spectra with $t/a = 1$, (i.e. with no grating) to divide out the strong baseline slope caused by free carrier absorption. A strong fundamental resonance is observed with weaker higher order resonances also present. All peaks shift to lower wavenumber with negative gate bias. The higher order resonances shift faster, so that the spacing between resonances decreases. The lines also get weaker as $n_s$ deplete.

Figure 21 presents experimental spectra of transmitted intensity for different applied gate voltages with both source and drain grounded. There are strong rapid oscillations due to Fabry-Perot resonance in the plane-parallel semiconductor substrate. At certain wavenumber positions indicated by arrows, we observe a near cancellation of the oscillations, indicating that the sample is absorbing at these wavenumbers. (That some of the signal is negative and that some absorption peaks appear with the wrong sign is attributed to the extremely weak throughput leading to poor phase correction of the single-sided interferogram.) For zero gate bias, two absorption resonances are observed, and by $V_g = -0.2$ V, a third absorption feature has emerged into the high end of the spectral range of the experiment. As negative gate voltage is applied, all features shift to lower wavenumbers and converge, in qualitative agreement with the calculated spectra. Also in agreement with the calculated spectra is the tendency for the lowest resonance to be stronger than the higher ones. Hence we attribute these features to the plasmon resonances.
Figure 20. Calculated transmittance spectra corrected for free carrier absorption at three different gate voltages at 22K.
Figure 21. Measured spectrum of intensity transmitted through gate region of HEMT. Plasmon absorptions (arrows) appear as the extinction of substrate Fabry-Perot oscillations.

**AlGaN/GaN Transmission Measurements**

Figure 22 shows the calculated absorption spectra of AlGaN/GaN heterostructure HEMT at $V_G = 0$V. Absorption instead of transmission on logarithmic scale is shown in order to remove the apparent higher FWHM for the first harmonic than that of the second.
Figure 22. Calculated absorption spectra of AlGaN/GaN device at gate voltage zero.

The device parameters are shown in an inset. Figure 23 exhibits the tunability of plasmonic resonances with the application of gate bias in the GaN device. Similar to InP device, resonances shift towards lower frequency with the charge depletion in channel. Figure 24 (a) exhibits the measured transmission spectra at different gate voltages. Figure 24 (b) shows the calculated spectra for the same system. Sheet charge carrier density is the fitting parameter for this set of calculations as shown in figure 23. The calculated plasmon absorption location matches closely with the measured ones. As evident in the calculated spectra for $V_g = -5$ and -6 volts, the third order resonance due to ratio $t/a = 1/3$. The validity of theory is preserved as in the measured spectra too, we do not observe any third order resonance.
Figure 23. Variation of sheet charge carrier density $n_s$ as a function of gate voltage $V_g$ for GaN system.

Figure 24. Demonstration of tunability of AlGaN/GaN device with gate voltage.

(a) (b)
**Photoresponse**

In photoresponse experiments, performed only on InGaAs/InP device, using the constant current biasing scheme with $I_{SD} = 0$, a negative photovoltage of order 10 mV was observed between source and drain coincident with the laser pulse. FEL induced current flowing from source to drain would account for the negative voltage. Increases in this voltage magnitude upon increasing negative gate bias are consistent with increases in source-drain resistance as channel depletion occurs. Previous DC IV curves taken at low source drain bias suggest a source-drain resistance of $1k \Omega$ under zero gate bias. This result allows one to infer a FEL induced current of approximately $9.2 \mu A$. Another feature was that the photoresponse changed sign and was much smaller in magnitude when the polarization was rotated to the vertical using a pair of polarizers sequentially at 45 and 90 degrees with respect to the horizontal. This gave a THz electric field polarized parallel to the grating stripes. During this observation the intensity on the sample was maintained constant.

The $\Delta V_{SD}$ was found to have a sub-linear dependence on laser pulse energy $P$, as shown in figure 25. At low powers, the data go as the square root of the pulse energy, but at higher powers the data approach a straight line. Normalization of the measured $\Delta V_{SD}$ by $P$ fails to correct adequately for shot-to-shot energy variations, such that significant artifacts appear in data so normalized. To reduce such artifacts, the measured $\Delta V_{SD}$ were normalized instead to a quadratic function $AP + BP^2$ of pulse energy $P$. The coefficients $A$ and $B$ were determined from a fit to $\Delta V_{SD}$ data measured in the unbiased device as a function of $P$. Figure 25 presents examples of these measurements. Independent data taken at the same wavenumber need not
coincide: Pulse energy at the sample for the same beam intensity changes with the alignment and focus conditions. Since these conditions were adjusted several times during the several days of experimentation, it is impossible to make any conclusion from figure 25 concerning the wavelength dependence of the photoresponse. Different fitting coefficients were determined for each curve and used to correct data taken under the same conditions. Experimental $\Delta V_{\text{SD}}$ points normalized in this way have positive sign.

![Figure 25](image)

**Figure 25.** Zero-bias photo response as a function of laser pulse energy at three different THz frequencies.

With $I_{\text{SD}} = 20 \, \mu\text{A}$ applied, the magnitude of the photoresponse increased, indicating a THz induced increase in channel resistance. Near pinch off, this increase (which we refer to as the photoconductive component in the total signal) exceeded the zero-bias photovoltage. Far from pinch off, the increase was negligible. Figure 26 presents the normalized $\Delta V_{\text{SD}}$ vs. gate bias $V_{\text{GD}}$ with and without source bias $I_{\text{SD}}$ for a FEL frequency of 12 cm$^{-1}$. Apart from some non-repeatable weak bumps and outliers, nothing like a resonance is observed in either curve.
Figure 26. Device photoresponse with and without current bias as a function of gate bias at a frequency of 12 cm⁻¹.

Figure 27 presents photoresponse data at a frequency of 17 cm⁻¹. According to figure 21, a resonance might be expected at a gate voltage of about -150 mV. However, due to the constant ISD biasing and a reluctance to allow VSD to exceed 0.5 V, the value VGD = -150 mV was unattainable. A strong feature observed once near a gate bias of -75 mV was unrepeatable.

Figure 27. Device photoresponse with (heavy lines) and without (light lines) current bias as a function of gate bias at a frequency of 17 cm⁻¹.

Figure 28 presents photoresponse data at a frequency of 19.5 cm⁻¹. According to figure 21, a resonance might appear at a gate voltage of about -80 mV, which is in range of the
experiment for constant $I_{SD} = 20 \mu A$ biasing. There may be a bump near this gate voltage, but it is very weak and could easily be noise.

Figure 28. Device photoresponse with (solid symbols) and without (open symbols) current bias as a function of gate bias at a frequency of 19.5 cm$^{-1}$.

Results for constant voltage bias, schematically shown in figure 12(b), are presented in figure 29 at frequency 17 cm$^{-1}$ for large load resistance and small bias, and also for small load and large bias. With this method of biasing, the photoresponse is positive. Here the photoresponse was best fit to a pulse energy dependence of $A\sqrt{P} + BP$, and hence the data is normalized by this function. The photo response is one order larger in the large load case. As mentioned above, the fundamental plasmon resonance occurs near $V_G = -150$ mV at this wavenumber (Fig. 14), but no resonance effect on transport is detected at this gate bias in figure 29.
Figure 29. Device photoresponse with constant voltage bias $V_S$ as a function of gate bias $V_G$ at frequency 17 cm$^{-1}$ for different bias $V_S$, different load resistance $R_L$, and in one case with a shunt capacitor.
CHAPTER FIVE: CONCLUSION

For the system AlGaN/GaN theoretically calculated values are exceedingly closer to the measured plasmon resonances. Figure 30 shows the comparison of experimental and calculated resonant values. The open symbols represents calculated resonant wavenumbers and solid symbols represents measured for \( a = 1.5 \mu m \) and \( t = 0.5 \mu m \) system of AlGaN/GaN HEMT at the temperature of 4K.

![Figure 30. Comparison of resonance wavenumber as a function of gate bias calculated (open symbols) with experimental data (solid symbols).](image)

In InGaAs/InP devices, we note two types of discrepancies between the calculated and observed resonances. These are in the ratios of the higher resonance frequencies to the fundamental frequency and in the absolute frequency values. According to Eq. (6), the ratios are affected only by the value of \( d/a \) and not by the value of \( n_s/m^* \). (Here, we consider the
uncertainties in the permittivities to be small, because all the end member values used in Eq. (5) are similar.

Figure 31 compares the predicted resonance frequencies (Eq. 6, open symbols) vs. $V_g$ for two different temperatures and for $p = 1, 2,$ and $3$ harmonics with the experimental observations (solid symbols). It is noted that the observed resonances occur at lower wavenumbers than predicted by a factor of up to $\sim 3$. At $12$ K, the sheet charge density is already depleted at -0.2 V gate bias, according to our transport measurements, but our experiment still gives evidence of plasmons. For this reason we believe that the sample temperature exceeded $12$ K during the transmission measurements.

Calculated ratios $\omega_p : \omega_1$ from Eq. (6) with the nominal $d/a$ value are $1.6, 2.1, 2.4,$ and $2.7$ for $p = 2, 3, 4, 5$, respectively. The observed ratios (figure 21) are approximately $2.0 \pm 0.1$ and $3.2$, where 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 for the same mode numbering.

![Figure 31. Comparison of resonance wavenumber as a function of gate bias calculated for two different temperatures (open symbols) with experimental data (solid symbols).](image)
If one supposes that only odd modes have been observed, as was the case in Refs. 3 and 14, then the observed ratio $2.0$ agrees better with the calculated value for $\omega_3/\omega_1$, but then the observed ratio $3.2$ is still significantly higher than the calculated $\omega_5/\omega_1$. Besides failing to give adequate agreement in the ratios, exclusion of evenly numbered modes is unphysical in the present case. In [45, 55], the grating duty cycle was $50\%$, and in that case the even-order terms vanish from the Fourier expansion of the local fields, so that even harmonics are not excited by them. The disappearance of even modes for a $50\%$ duty grating was clearly demonstrated by calculation in [56]. In the present work, the grating duty was far from $50\%$ (figure 2), and even modes are expected.

Closer agreement between calculated and observed ratios is achieved by supposing a smaller $d/a$ value. For sufficiently small $d/a$, the ratios increase linearly in $p$ since then the Coth term in Eq. 6 goes as $1/p$. This would give ratios of $2$ and $3$ in close agreement with observations. Values of $d/a$ that achieve this are below $\sim0.01$, while the nominal value was $0.089$. Manufacturer-specified layer thicknesses (Figure 1) should be accurate, and selective etching and step profiling support the nominal $d$ value $44.5$ nm. The $a$ value might be replaced by the gate-aperture dimension $L$ as the characteristic length that determines the plasmon wavevector, and since $L$ exceeds $a$ by $390$-fold, such replacement is beyond that necessary to achieve ratios going as $p$. However, this replacement causes serious problems for the absolute frequencies, as explained next.

The second type of discrepancy is that the measured resonances fall below positions calculated using nominal parameter values. With the nominal zero-bias $n_s/m^*$ value, smaller calculated frequencies can be achieved by reducing $d$ or increasing $a$, (which also improves the
ratios). As indicated above, replacing $a$ by $L$ puts the fundamental a factor $\sim 250$ below the lowest observed resonance, so that the observed resonances would have to correspond to high orders, leading again to ratio problems. This might be remedied by a simultaneous 250–fold [44] increase in $n_s/m^*$, but this seems unreasonable, as argued below. Instead, taking again the nominal $a$ and $n_s/m^*$ values, fair agreement for both absolute frequencies and their ratios is achieved by reducing $d$ to $\sim 5$ nm. Although it seems unreasonable to reduce the gate-2deg distance so much, we note that this is approximately the thickness of the undoped InAlAs setback above the 2deg.

We next consider the probable uncertainty in $n_s/m^*$. We have noted that the $m^*$ value could be 50% higher than the nominal value due to wavefunction penetration into the barrier material. IV measurement gave $n_s$ values using simplified equations that nevertheless should give a better than order-of-magnitude estimate of $n_s$. Independent Hall measurement gave a 40% higher $n_s$, but the very different geometries of the HEMT and the Hall sample leave this value of questionable relevance. Capacitance versus voltage measurements might have been used to estimate $n_s$, but this technique was not used here because of ambiguities due to trapping centers and the extent of dopant activation. All these considerations suggest that the nominal $n_s/m^*$ value is known with better than order-of-magnitude accuracy.

It may be that the heavy doping of nearly half of the 44.5 nm of InAlAs layer has a significant effect unaccounted for by the theory, which was developed for silicon MOSFETs where the layer separating the gate from 2deg is SiO$_2$. The doping, which ends $\sim 5$ nm above the 2deg, coincides with the effective value for $d$ where calculated value is very close to the observed ratio and frequency. This is demonstrated in figure 32 where both frequency ratios of higher harmonics to fundamental and absolute frequencies are plotted against grating period $a$,
and $d$, the 2deg depth. The modification of the theory [50] to account for the presence and effects of unscreened ionized donor impurities on the fields and charge distribution of the 2DEG is left, as of now, for future work and we leave it as a question for theoreticians. In summary, detection of two-dimensional plasma oscillations in the electron gas of an InGaAs/InP HEMT device has been reported. This device utilizes grating coupling of incident radiation to plasmon modes in the 2-deg. Such a device might find application as a voltage tunable band-blocking filter. Alternatively, potential changes in device conductance caused by resonant absorption might be used for tunable THz detection.

Figure 32. Variation of frequency ratio and absolute frequency with grating period and 2deg depth.
In summary, two-dimensional plasma oscillations in the electron gas of an InGaAs/InP HEMT device have been clearly seen in far-IR transmission spectra. An initial search for an effect of such resonances on transport, using a mm-wave free electron laser, was less conclusive. We suggest that the effect may be masked or altered by the large non-resonant non-linear response to the incident THz radiation and by noise or artifacts induced by pulse energy-variations of the free electron laser. The metallization pattern that was designed with transmission measurements in mind may enhance that response by acting as an antenna.
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