Plasma based Terahertz Devices

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***Abstract*—We discuss the dispersion relation of a thin sheet of plasma embedded in a heterogeneous semiconductor environment. Existence of a surface wave in the structure is investigated. The suitability of III-V compounds and perovskite structured oxide materials for plasma based terahertz devices is investigated by a comparison between prevalent structures of each kind.**

I. Introduction

The past decade has seen tremendous growth in the field of two-dimensional materials and its subsequent applications in electronics. Our perception of materials existing only in volumetric sense is also changing. Modern semiconductor technology has enabled deposition of materials with thickness smaller than the nanoscale. When two slightly different semiconducting compounds are stacked in a layered fashion, the interface results in what is commonly called a heterojunction where the electrical properties vastly differ from the bulk materials. A highly charged and extremely thin region called the two-dimensional electron gas (2DEG) is consequently formed that has in some cases shown high temperature superconductivity [1]. In this paper, we present the basic theory of wave propagation in the 2DEG by treating it as a thin sheet of plasma. We show that the classical electromagnetic theory can explain some of the extraordinary properties of thin materials.

II. Theory

A. Derivation of Dispersion Relation

Consider two dielectric half-space regions of permittivities ε_1 and ε_2, separated by an infinitesimally thin sheet of charge at $z = 0$ that represents an idealized 2DEG in which current flows in only one direction. The field expressions due a transverse magnetic (TM) incident plane wave in region 1 $(z > 0, \varepsilon_1)$ are:

$$\mathbf{E}_1 = (\hat{\mathbf{x}} E_{x1} + \hat{\mathbf{y}} E_{z1})\, e^{-j(k_x x + k_{z1} z)}, \tag{1a}$$
$$\mathbf{H}_1 = \hat{\mathbf{y}} H_{y1} e^{-j(k_x x + k_{z1} z)} \tag{1b}$$

Similarly, in region 2 $(z < 0, \varepsilon_2)$, the fields are:

$$\mathbf{E}_2 = (\hat{\mathbf{x}} E_{x2} + \hat{\mathbf{y}} E_{z2})\, e^{-j(k_x x - k_{z2} z)}, \tag{2a}$$
$$\mathbf{H}_2 = \hat{\mathbf{y}} H_{y2} e^{-j(k_x x - k_{z1} z)}. \tag{2b}$$

The quantities k_x and k_{zi} for $i = 1, 2$ are the x and z directed propagation constants respectively, related by the dispersion equation:

$$\begin{aligned} k_{zi} &= \sqrt{k_i^2 - k_x^2} \\ &= \sqrt{\left(\frac{\omega}{c}\right)^2 \varepsilon_i(\omega) - k_x^2} \end{aligned} \tag{3}$$

where k_i is the wavenumber of the corresponding region. The dispersive dielectric constants $\varepsilon_i(\omega)$ are based on a Lorentz oscillator model:

$$\varepsilon(\omega) = \varepsilon^{\infty} + \prod_i \frac{\omega_{li}^2 - \omega^2 - j\gamma_{li}\omega}{\omega_{ti}^2 - \omega^2 - j\gamma_{ti}\omega} \tag{4}$$

where i is the number of resonances, ε^{∞} is the high frequency limit value of dielectric constant, ω_{ti} and ω_{li} are the i-th low and high phonon frequencies and the corresponding γ is the damping constant. Applying boundary conditions by maintaining the continuity of tangential field components at the interface $z = 0$ yield:

$$E_{x1} = E_{x2} = E_x, \tag{5a}$$
$$H_{y1} - H_{y2} = J_s \tag{5b}$$

where J_s is the surface current due to the sheet of charge. For a TM mode, H is related to E by:

$$\mathbf{H} = \frac{1}{\eta_{TM}} \hat{\mathbf{n}} \times \mathbf{E} \tag{6}$$

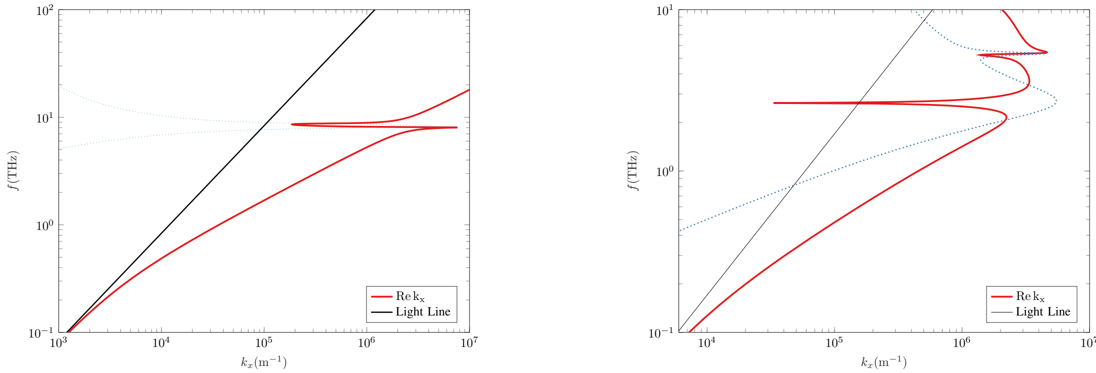
where η_{TM} is the TM mode wave impedance equal to $k_z/\omega\varepsilon$. Since the current flow is in one-direction, the surface current J_s in (5b) is related to the electric field and surface conductivity σ_s by Ohm's law:

$$J_s = \sigma_s E_x \tag{7}$$

In the microwave and terahertz regions, the surface conductivity can be approximated by a Drude-type formula:

$$\sigma_s(\omega) = \frac{N_s e^2 \tau}{m^*} \frac{1}{1 + j\omega\tau} \tag{8}$$

where e and m^* are the effective charge and mass of an electron respectively, N_s is the surface-charge density, and the scattering time τ is the reciprocal of damping constant



(a) Case A

(b) Case B

Fig. 1. Dispersion relation of 2DEG embedded in region 2 of the heterostructure. Solid line: real part, dashed line: imaginary part

γ_l for the low phonon frequency at first resonance. From Eqs. (5)-(7), we obtain the TM mode dispersion relation:

$$\frac{\varepsilon_1(\omega)}{k_{z1}} + \frac{\varepsilon_2(\omega)}{k_{z2}} = -\frac{\sigma_s}{\omega} \tag{9}$$

In the terahertz region, the surface conductivity (8) can case be approximated as [2]:

$$\sigma_s(\omega) \approx \frac{N_s e^2}{j m^* \omega}. \tag{10}$$

When the 2DEG is in a homogeneous environment. i.e., $\varepsilon_1 = \varepsilon_2$, Eq. (**??**), is simplified into:

$$\frac{2\varepsilon_1(\omega)}{k_{z1}} \approx -\frac{N_s e^2}{j m^* \omega^2} \tag{11}$$

From (11) and (3), we obtain a solution for the propagation constant k_x:

$$k_x^2 \approx \left(\frac{\omega}{c}\right)^2 \varepsilon_1(\omega) \left[1 + \left(\frac{2\omega^2}{\omega_p}\right)^2 \varepsilon_1(\omega)\right] \tag{12}$$

where ω_p is the 2DEG plasma frequency given expressed as:

$$\omega_p = \sqrt{\frac{4\pi e^2 N_s}{m^* c}}. \tag{13}$$

where c is the speed of light. For a semiconductor heterojunction environment, an exact solution of (9) is often cumbersome due to the complex arguments of the square root function. However, when the propagation constant k_x is much larger than the material wave-vectors k_i, which is the case for a non-radiating wave, the solution can be accurately approximated as [3]:

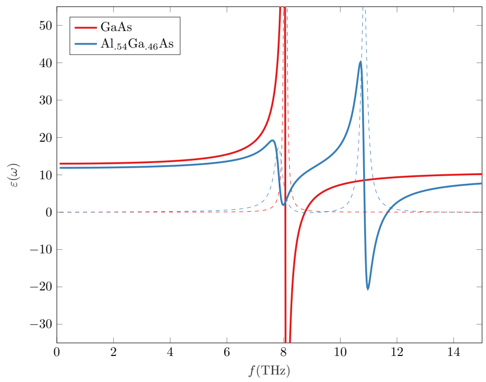
$$k_x \approx -\varepsilon_1(\omega) + \varepsilon_2(\omega) \frac{j\omega}{\sigma_s(\omega)} \tag{14}$$

III. Results and Discussion

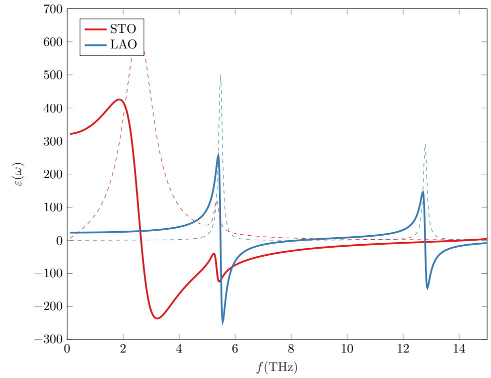
In this section, we compare two different 2DEGs formed at the heterojunction of first III-V compounds and, second in a perovskite structured oxide interface. We particularly consider a Gallium Arsenide/Aluminum Gallium Arsenide (GaAs/AlGaAs) case which is most commonly used in microwave devices. A surface charge density N_s of $10^{11}\mathrm{cm}^{-2}$ with effective mass of $.07m_e$ is assumed where m_e is the electron mass. The latter involves a Strontium Titanate/ Lanthanum Aluminate based 2DEG abbreviated as STO/LAO with a metal-like carrier density of $10^{14}\mathrm{cm}^{-2}$ and effective mass of $3m_e$ [4]. From here onwards, we identify the structures discussed above by cases A and B respectively. The dispersion relations for both cases are shown in Fig. 1 where the 2DEG is embedded in region 2. The lower part of the curve lies in the non-radiative plasmon region followed by an anomalous dispersion region and above that a Brewster mode radiative region. The plasmon region lies to the right of the light line and therefore, it is a slow wave region. Of particular significance is the subsequently much shorter wavelength of plasmons than light that prevents them to radiate from a flat planar surface. In other words, the plasma waves are tightly confined to the 2DEG where they propagate along the interface. This mechanism has led to waveguiding structures with highly miniaturized dimensions [5]. As seen in Fig. 1, the propagation constant in case B is at least an order greater than case B. This is due to the higher concentration of surface charges. To investigate the existence of surface waves, the following condition is necessary [6]:

$$\varepsilon_1(\omega) \cdot \varepsilon_2(\omega) < 0 \tag{15}$$

For this purpose, the dielectric functions of the materials used are shown in Fig. 2 calculated from (5a). The material parameters for GaAs, $\mathrm{Al_xGa_{1-x}As}$ with $x = .54$ and STO are taken from [7], whereas the data for LAO is taken from [8]. As an example, GaAs parameters are listed in Table. I. It can be observed in Fig. 2b, that within the frequency range of $3-5$THz, the necessary condition (15) holds true only for case B. This suggests that a 2DEG based on materials used in case

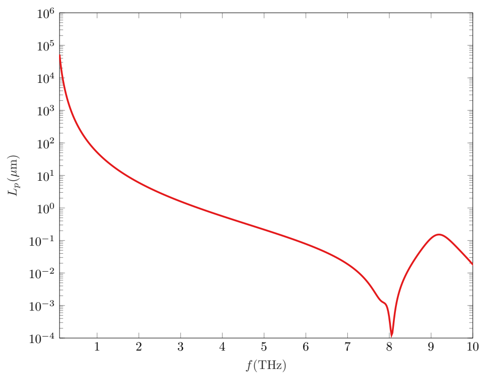


(a) Case A

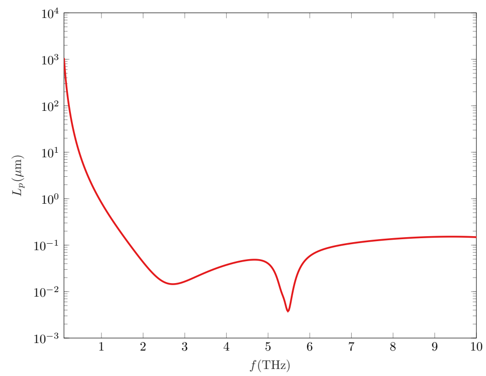


(b) Case B

Fig. 2. Dielectric Functions of the materials in bulk form. Solid line: real part, dashed line: imaginary part



(a) Case A



(b) Case B

Fig. 3. Propagation Lengths of the 2DEG plasma waves

B supports surface waves and is a better choice for guiding devices. The complex permittivity of GaAs is plotted in Fig. **??**

TABLE I
GaAs Material Properties

ε^0	12.9
ε^∞	11.0
ω_t	5.52×10^{13}rad/s
ω_l	5.06×10^{13}rad/s
Γ	4.52×10^{11}rad/s
m^*	$.063m_e$
τ	1.3889×10^{-12}s

where the real part changes sign at the plasma frequency. The result is shown in Fig. **??**. The lower part of the curve lies in the non-radiative plasmon region followed by an anomalous dispersion region and above that a Brewster mode radiative region. The plasmon region lies to the right of the light line and therefore, it is a slow wave region. Of particular significance is the much shorter wavelength of plasmons than light preventing from radiating from a planar surface. A limiting value of the wavelength confinement can be estimated from:

$$\frac{\lambda_t}{\lambda_{sw}} \approx \sqrt{\varepsilon_1(\omega_t) + \varepsilon_2(\omega_t)} \tag{16}$$

where $\lambda_t = 2\pi c/\omega_t$ is the start wavelength of the dispersive region that corresponds to the first phonon resonance in the dielectric functions shown in Fig. 2 dispersive region. We have calculated the ratios of 1.32 and 27.3 for cases A and B respectively.

The decay of the plasma wave along the interface is determined by the propagation length defined as:

$$L(\omega) = \frac{1}{\mathrm{Im}(k_x(\omega))} \tag{17}$$

which is plotted in Fig. 3. Although the plasma waves travel farther in GaAs based 2DEG, the lower distance in an STO based 2DEG, which can be attributed to higher dielectric constant of STO is still very large considering the dimensions of devices at terahertz frequency range. This behavior is similar to surface plasmons found at metal-dielectric interfaces at optical frequencies [9].

IV. Conclusion

In this paper, we have presented the basic theory of plasma wave propagation in the 2DEG. A comparison between III-V class of materials and perovskite based oxides has been done by an example. The wave propagation phenomenon has been analysed and the result show that oxide-based materials outperform traditional III-V compounds in the terahertz frequency range.

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