On the Existence of Terahertz Plasmons in Two-dimensional Semiconductor Heterostructures

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In this paper, we study the plasmonic activity in a semiconductor heterostructure which is found in a high electron mobility transistor. Transmission line techniques are used to describe the dispersion diagrams of the transistor semiconductor stack. We show that the existence, as well as the propagation characteristics of plasmons in the terahertz frequency range are subject to the electronic properties of the semiconductor materials. Specifically, the quality of the plasmons is dictated by the complex valued conductivity of the two-dimensional electron gas, formed at the interface of two semiconductor materials having slightly different bandgaps. The existence of surface waves is investigated using the transverse resonance method and it is established that the complex conductivity of the two-dimensional electron gas with a negative imaginary part yields surface plasmons in the terahertz frequency domain.

An increasingly growing interest in the terahertz (THz) frequency domain (0.1-10 THz) has stimulated the development of stable, fast and sensitive generators and detectors. The interdisciplinary nature of research in the THz area has incorporated the technologies of optics as well as microwave electronics. Two-dimensional (2D) electron systems that can be broadly classified as van der Waal's structures are engineered to exhibit extraordinary electromagnetic properties. More importantly, they can be easily integrated with the existing silicon-based electronics and implemented using the conventional fabrication techniques used in transistor technologies. The 2D plasmons in the presence of grating structures can subsequently be used as THz detectors and emitters [1]. The fact that, the resonant frequency of the plasmons can be tuned by varying the gate voltage of the transistor highlights the applications in such as terahertz photodetection [2].

In this paper, we present a simple method to compute the dispersion relation of the 2D plasmons. The epitaxially grown multilayer structure of the transistor is studied through a transmission line (TL) analogue, in which the infinitesimally thin conductive layer of plasmons is modeled as a shunt admittance. Using the transverse resonance method, the dispersion relation is written as [3]

$$Y^{\uparrow}(z_0) + Y^{\downarrow}(z_0) + Y_{\sigma} = 0 \tag{1}$$

where $Y^{\uparrow}(z_0)$ and $Y^{\downarrow}(z_0)$ are the up- and down-looking TL admittances from the 2DEG located at $z = 0$, and Y_{σ} is described by the conductivity of the 2DEG. For a complex valued solution of (1), traditional root-finding methods such as Newton-Raphson which need a first guess may lead to non-physical solutions. Therefore, a robust complex root-finding algorithm is needed in which convergence to physically practical results, when an initial region is specified. The results show that the propagation constant obtained as a solution of (1) is much larger than the corresponding free-space wavenumber, therefore illustrating a subwavelength wave phenomenon in the 2D region.

1. A. El Fatimy, N. Dyakonova, Y. Meziani, T. Otsuji, W. Knap, S. Vandenbrouk, K. Madjour, D. Théron, C. Gaquiere, M. A. Poisson, S. Delage, P. Prystawko, and C. Skierbiszewski, "AlGaN/GaN high electron mobility transistors as a voltage-tunable room temperature terahertz sources," *Journal of Applied Physics*, vol. 107, no. 2, p. 024504, 2010.

2. F. Wang, Z. Wang, L. Yin, R. Cheng, J. Wang, Y. Wen, T. A. Shifa, F. Wang, Y. Zhang, X. Zhan, and J. He, "2D library beyond graphene and transition metal dichalcogenides: a focus on photodetection," *Chem. Soc. Rev.*, vol. 47, pp. 6296–6341, 2018.

3. L. B. Felsen and N. Marcuvitz, Radiation and Scattering of Waves, *IEEE Press Series on Electromagnetic Wave Theory*. Wiley-IEEE Press, 1994.