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PLASMONIC MODE CONFINEMENT IN InAs–SiO$_2$–Si WAVEGUIDE IN TERAHERTZ REGION

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The dispersion relation of a novel semiconductor-gap-dielectric waveguide in terahertz range are investigated. It is shown that InAs–SiO$_2$–Si structure supports strongly confined guided mode with a sizes ~0.0016 $\lambda \times 0.02\,\lambda$ at 1 *THz*.

Keywords: terahertz, waveguides, surface plasmons.

Introduction. Terahertz (THz) radiation shows great potential in a broad range of technological areas, such as the medical diagnostics, sensing, product quality control, or security imaging [1]. The emergence of compact THz circuits requires the design of functional elements of the size smaller than THz wavelengths. In the optical range, the surface plasmon polaritons (SPPs) have demonstrated excellent capabilities for achieving subwavelength confinement of electromagnetic energy, though its propagation on the metal surface is accompanied with large losses [2]. Recently it was shown that at the propagation of subwavelength confined optical waves in the waveguide composed of a dielectric cylinder and a plane metallic surface the losses were notably low. Such a plasmonic waveguide restricts the field confinement within a small region and at the same time ensures a longer propagation length than those of the surface plasmon on the metal surface [3].

The main goal of this report is to investigate this new waveguiding structure in THz range. Note that the idea of surface plasmon polariton (SPP) mode is not easily transferable from optics to the THz range. The SPPs are not inherently generated in the terahertz region, because the majority of metals have high absorption loss and act like perfect electric conductors. To overcome this problem, artificial periodic structures is introduced to spoof SPPs [4]. By configuring the geometry of metal surface a propagation of terahertz SPP over the metallic periodical structure shall be accomplished.

An alternative approach is based on the application of such semiconductors as Si and GaAs [5]. As the carrier densities in semiconductors are much lower than those in metals, the plasma frequency is much smaller, being typically at the mid- or far-infrared regions. Therefore, the permittivity of semiconductors at THz is comparable to that of metals at optical frequencies.

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In this paper, for the first time to our knowledge, a THz plasmon waveguide on the basis of InAs is considered. It is especially interesting as InAs is known to be the best semiconductor THz emitter [1]. Therefore, it proves possible to integrate THz generator and waveguide in single compact unit.

Waveguide Structure and Dispersion. The waveguide structure studied here is d-thick low refractive index (LRI) gap layer sandwiched-in a semiconductor with metal-type permittivity $\dot{\varepsilon}_m = \varepsilon'_m + i\varepsilon''_m$ ($\varepsilon'_m < 0$), and a high refractive index (HRI) lossless dielectric on the other side. The structure is schematically shown in Fig. 1 and in what follows it is referred to as the semiconductor-gap-dielectric (SGD) waveguide.

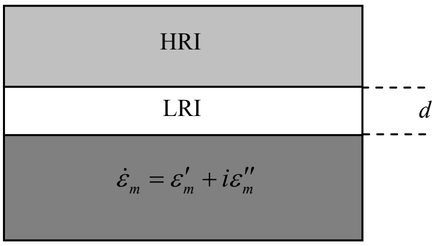

Fig. 1. Schematic view of semiconductor--gap-dielectric (SGD) structure.

To calculate the complex effective index $\dot{n}_{eff}$, the dispersion equations for TM modes in three-layer system have been used. According to [6] the dispersion equations for TM modes is given by

$$e^{-2qd}\left(\frac{q}{\varepsilon_g}-\frac{p}{\varepsilon_d}\right)\left(\frac{q}{\varepsilon_g}-\frac{r}{\varepsilon_m}\right)=\left(\frac{q}{\varepsilon_g}+\frac{p}{\varepsilon_d}\right)\left(\frac{q}{\varepsilon_g}+\frac{r}{\varepsilon_m}\right), \tag{1}$$

where

$$p=\frac{2\pi}{\lambda}\sqrt{n_{eff}^2-\varepsilon_d}\,,\quad q=\frac{2\pi}{\lambda}\sqrt{n_{eff}^2-\varepsilon_g}\,,\quad r=\frac{2\pi}{\lambda}\sqrt{n_{eff}^2-\varepsilon_m}\,, \tag{2}$$

ε_g and ε_d are the dielectric permittivities of gap and dielectric cover respectively.

The dispersions of both $n_{eff} = \mathrm{Re}(\dot{n}_{eff})$ and propagation length $L = 1/k_0\,\mathrm{Im}(\dot{n}_{eff})$ for InAs–SiO$_2$–Si waveguides with gap thicknesses of $d = 0.2$ μm and $d = 0.5$ μm are presented in Fig. 2.

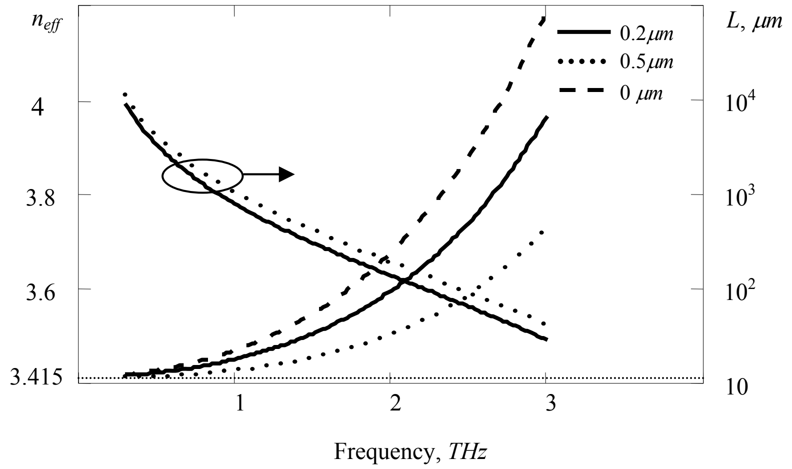

Fig. 2. Dependence of mode index and propagation length on frequency in InAs–SiO$_2$–Si waveguide for different thicknesses of silica layer: 0.5 μm (solid lines), 0.2 μm (dotted lines) and zero (dashed line) that is equivalent to InAs–Si structure.

The permittivity of InAs has been modeled by the Drude formula with plasma frequency f_p = 5.3 *THz* and damping rate γ = 1.1 *THz* [7]. The dielectric constants of SiO_2 and high-resistivity Si were taken to be n_{SiO_2} = 1.95 and n_{Si} = 3.415 [8]. As is seen in Fig. 2, in the frequency range of 0.3–3 *THz* the mode index of InAs–SiO_2–Si waveguide is higher than n_{Si}. This means that the plasmon mode is propogates in a narrow silica gap having, for example, the thickness of 0.5 μm. As a result of decreased thickness of gap the value of n_{eff} is increased and, therefore, the mode may be confined in a narrower size gap. However, the reduction in gap thickness entails an increase of losses. The case of d = 0.5 μm when $\Delta n = n_{eff} - n_{Si} \approx 0.013$ and the propagation length L = 1.05 *mm* may be regarded as providing an optimal confinement-to-loss ratio at 1 *THz*.

The field strength distributions along the vertical direction of InAs–SiO_2–Si structure for frequency of 1 *THz* and gap thicknesses d = 0.5 μm are presented in Figs. 3, a and b.

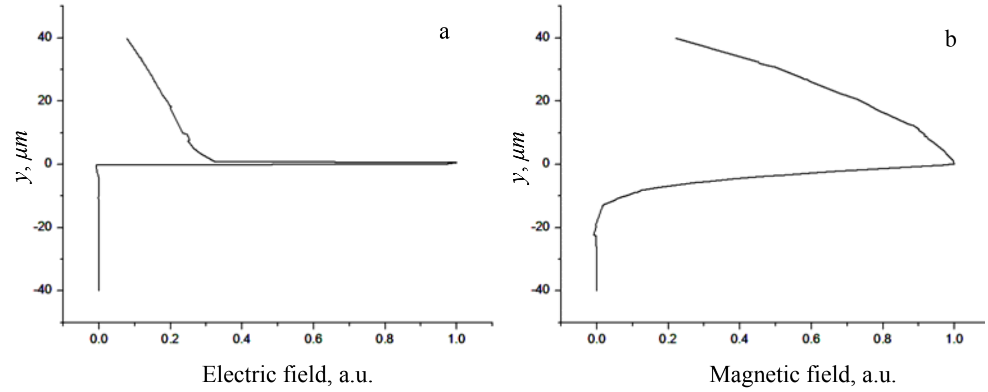

Fig.3. Strength of normal component of electric field (a) and tangent component of magnetic field (b).

As is seen in Fig. 3, a, the electric field of the mode is significantly enhanced in the gap layer, sharply drops at the gap interface, and exponentially decays in InAs substrate (having $\varepsilon'_m < 0$) and Si-cover. The increase of gap thickness results in longer field penetration in Si-cover.

Lateral Confinement. As was already mentioned n_{eff} is decreased as a result of increasing the gap thickness d. Reverting to the case of InAs–SiO_2–Si waveguide we obtain that when f = 1 *THz* the condition $n_{eff} > n_{Si}$ is observed up to the values of thickness $d < d_m$ = 1.4 μm. Therefore, one can confine the THz beam in the lateral direction by scaling up the values of gap thickness from very small $d = d_0$ to $d = d_m$ that is easily realized by reshaping the Si-cover into cylindrical form. The lateral confinement may be even stronger with rectangular section Si-cover that is an analogue of step-index waveguide having high refractive index contrast.

The field distributions in these waveguides have been simulated by using the COMSOL commercial software package. The intensity distributions for cylindrical Si-cover with radius of 20 μm and for rectangular one with 5 μm width are illustrated in Figs. 4, a and b.

The highest intensity is represented by black color and lowest – by white. In both the cases the vertical size of the mode is approximately equal to the gap thickness $d_0 = 0.5\ \mu m$, which corresponds to $0.0016\ \lambda$. The full width at half maximum in the intensity distribution along the horizontal direction is 12 μm for cylinder with 20 μm radius and is 6μm ($0.02\ \lambda$) for 5 μm-wide right-angle prism.

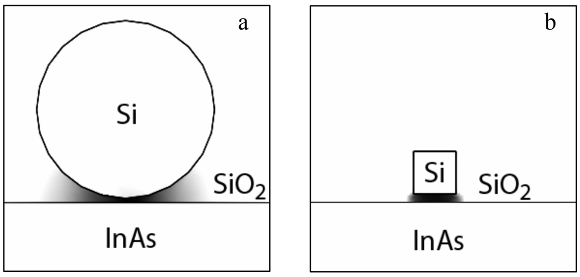

Fig. 4. Intensity distribution for cylindrical (a) and rectangular (b) forms of Si-covers.

Conclusion. The dispersion relation of a novel plasmonic InAs–SiO_2–Si waveguide is investigated in terahertz range. It is shown that the waveguide can support extremely strong confined guided mode (with the size $\sim 0.0016\ \lambda \times 0.02\ \lambda$ or mode area $3.2\times10^{-5}\ \lambda^2$ at 1 *THz*) for relatively long propagation length ~1 *mm*.

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