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A structure for enhanced terahertz emission from a photoexcited semiconductor surface

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Abstract A structure that can provide enhancement of terahertz emission from a semiconductor surface excited with femtosecond laser pulses is proposed. The structure consists of a semiconductor layer on a Si substrate with metal coating on the upper surface of the layer and a Si lens attached to the bottom of the substrate. The semiconductor is excited through a hole in the coating and emits terahertz radiation through the substrate lens. We demonstrate theoretically that the proposed structure can increase the terahertz yield by orders of magnitude as compared to the previously used schemes of terahertz emission from a semiconductor surface.

1 Introduction

Terahertz emission from semiconductor surfaces excited with above-bandgap femtosecond laser pulses is a widely used technique of terahertz generation for terahertz time-domain spectroscopy [1, 2] and novel promising applications, such as detection of explosive and biological hazards [3], nondestructive inspection of pharmaceutical tablets [4], etc. The advantages of this technique are its simplicity and ability to operate with non-amplified lasers.

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Terahertz emission from a semiconductor surface is generated by transient electric dipole created in a thin subsurface layer by fast separation of photoexcited electrons and holes driven either by the surface built-in electric field, as in GaAs [2], or by the different mobilities of the two types of carriers, as in InAs (the photo-Dember effect [5]). In both mechanisms, the dipole is oriented perpendicularly to the surface, and such an orientation creates the problem of extracting the radiation emitted by the dipole within a material (semiconductor) of high refractive index [6].

To increase the emission from the dipole to vacuum, several approaches have been proposed. One of them is imposing a large (of several Tesla) magnetic field on the semiconductor surface. The field deflects the orientation of the dipole from the surface normal, thus, increasing an overlap between the internal radiation pattern of the dipole and the emission cone at the semiconductor-air boundary [7–10]. For example, a 20 times enhancement in the emitted terahertz power was achieved experimentally for a 1.7 T [8] and 1 T [9] magnetic field applied to InAs. However, magnetic-field-enhanced emitters require large magnets; this limits the use of such emitters in many applications.

A simpler way is putting a coupler (prism or lens) onto the semiconductor surface. For example, using a GaAs prism provided a 20 times enhancement in the emitted from InAs terahertz power as compared to a bare InAs emitter [6]. Similarly, putting a MgO lens onto an InAs surface resulted in a 50 times enhancement in the terahertz power [11].

All the above-mentioned schemes of enhanced emission operate in the reflection geometry—terahertz radiation is collected at the same side of the semiconductor surface where the incident and reflected laser beams propagate. More convenient for practical applications may be the transmission geometry, in which a semiconductor layer is excited from the one side, whereas terahertz radiation is collected at the opposite side of the layer. Recently, such a geometry was used to explore terahertz emission from thin InAs films grown on Si substrates [12]. For efficient outcoupling of the transmitted terahertz radiation, it was proposed to attach a hemispherical Si lens to the bottom of the Si substrate [13]. In fact, using the transmission geometry with a substrate lens is similar to the conventional design of a photoconductive antenna [14]. The only difference is in the orientation of the emitting dipole—in photoconductive antennas, the dipole is tangential, rather than normal, to the semiconductor surface.

In this paper, we develop a further improvement of the transmission scheme. In addition to a substrate lens outcoupler, we propose to coat the upper surface of the semiconductor layer with a metal and excite the semiconductor through a small (as compared to the terahertz wavelength) hole in the coating. The terahertz waves reflected from the coating will experience an overturn of the tangential to the coating component of the electric field and, therefore, will interfere constructively with the terahertz waves emitted to the substrate lens directly from the semiconductor layer (the layer is assumed to be thin as compared to the terahertz wavelength). This effect, as we show below, can greatly enhance the terahertz yield.

2 Generation scheme and approach

The geometry of the structure and generation scheme are shown in Fig. 1. A thin layer ($0 < z < d$, $d \sim 100$–500 nm) of a semiconductor is arranged on a Si substrate with Si lens attached to the bottom of the substrate. The layer is coated with a metal (that can be treated as a perfect conductor in the terahertz range) and excited through a hole in the coating. The diameter of the hole (a few tens of microns) is assumed to be much smaller than the terahertz wavelength, therefore, an effect of the hole on the generated terahertz waves is negligible and the coating can be considered as a continuous one. The small size of the excitation spot allows us also to neglect the phased array effect [14] and model the photoinduced source of terahertz radiation as a point electric dipole placed below the semiconductor surface (at $z = 0+$). The incidence angle of the pump laser beam may be chosen equal to the Brewster angle to maximize the dipole moment. We neglect a weak dispersion of the structure's materials (semiconductor and Si) and treat the dipole as a monochromatic one with a moment $\mathbf{p} = \mathbf{z}_0 p \exp(i\omega t)$. Thus, we arrive at the problem of calculating the radiation emitted from a point monochromatic dipole in a three-layered metal–semiconductor–Si structure. The terahertz refractive indices of the semiconductor and Si are assumed to equal n_1 and n_2, respectively (Fig. 1).

The problem of calculating the far field radiated in an arbitrary direction θ (Fig. 1) by a z-directed dipole embedded inside the semiconductor layer can be reduced, by means of the Lorentz reciprocity theorem, to that of calculating the z-directed electric field produced at the dipole location by a plane wave impinging on the semiconductor layer from the same direction (see, e.g., [15]). Using this approach we obtain the time-averaged power radiated by the dipole to Si within unit solid angle into direction θ,

$$P(\theta) = \frac{\omega^4 p^2 n_2^5 T_{21}^2 \sin^2\theta}{2\pi c^3 n_1^4 |1 + R_{21} e^{-2i(\omega/c)n_1 d\cos\theta_0}|^2}, \tag{1}$$

where

$$R_{21} = \frac{n_1\cos\theta - n_2\cos\theta_0}{n_1\cos\theta + n_2\cos\theta_0}, \quad T_{21} = \frac{2n_1\cos\theta}{n_1\cos\theta + n_2\cos\theta_0} \tag{2}$$

are the reflection and transmission coefficients on the Si–semiconductor boundary, respectively, and the propagation angle of a terahertz wave in the semiconductor θ_0 is related to θ by the Snell's law $\cos\theta_0 = \sqrt{1-(n_2/n_1)^2\sin^2\theta}$.

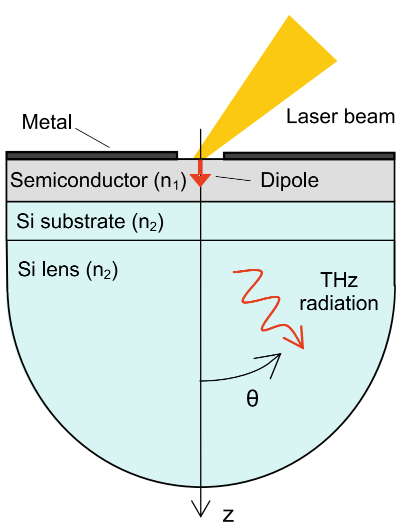

Fig. 1 Geometry of the structure and generation scheme

3 Results and discussion

Figure 2 shows $P(\theta)$ for the structure with InAs layer of the thickness $d = 500$ nm as a semiconductor (curve 1). We use $n_1 = 3.8$ for InAs and $n_2 = 3.4$ for Si. The frequency is $\omega/(2\pi) = 1$ THz in Fig. 2, however, $e^{-2i(\omega/c)n_1 d\cos\theta_0} \approx 1$ in (1) due to small d for all frequencies of interest $\omega/(2\pi) \le 3$ THz and, therefore, the normalized to maximum angular distribution $P(\theta)$ is practically independent of ω. The corresponding angular power distributions for an air–InAs–Si structure (a bare InAs layer on a Si substrate [12]) and GaAs–InAs–air structure (an InAs layer attached to a GaAs

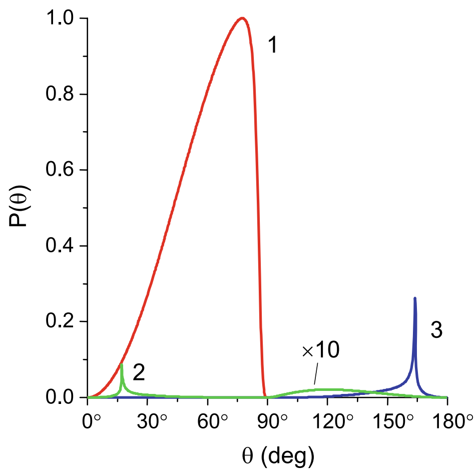

Fig. 2 Angular power distributions $P(\theta)$ for the present metal–InAs–Si structure (curve 1), air–InAs–Si structure (curve 2), and GaAs–InAs–air structure (curve 3). All curves are normalized to the maximum of $P(\theta)$ for the metal–InAs–Si structure. The angles $\theta > 90°$ correspond to the emission to the upper half-space $z < 0$ (Fig. 1), the curve 2 in this interval has been enlarged by a factor of 10. The thickness of the InAs layer is $d = 500$ nm and the frequency is $\omega/(2\pi) = 1$ THz for all curves

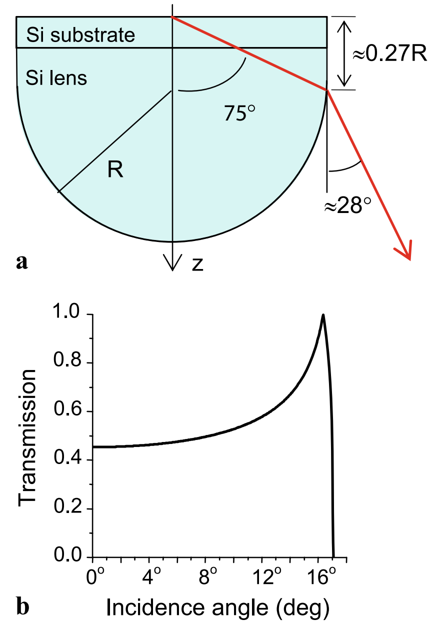

Fig. 3 (**a**) Design of the extended hemispherical lens and ray-tracing diagram. The ray at maximum emission angle $\theta = 75°$ is incident on the edge of the lens and emerges at ≈28°. (**b**) Amplitude transmission coefficient at the Si–air boundary as a function of the incidence angle

prism [6]) are shown in Fig. 2 for comparison (curves 2 and 3, respectively). The latter distributions were calculated using the same approach based on the Lorentz reciprocity theorem as above; the refractive index of GaAs at terahertz frequencies was taken equal to 3.6. Curves 2 and 3 resemble the angular power distributions for a dipole located near an interface of two dielectrics (Fig. 3 in [16]). This can be explained by a relatively small difference in the refractive indices of InAs and Si and of InAs and GaAs in air–InAs–Si and GaAs–InAs–air structures, respectively.

According to Fig. 2, the proposed metal–InAs–Si structure provides a significant enhancement in the terahertz emission as compared to the reference structures [6, 12]. The maximum power per unit solid angle for the metal–InAs–Si structure (curve 1 in Fig. 2) is more than two orders of magnitude higher as compared to the emission from an air–InAs–Si structure to the air (curve 2 at $\theta > 90°$ in Fig. 2), an order of magnitude higher as compared to the emission from the air–InAs–Si structure to the Si substrate (curve 2 at $\theta < 90°$ in Fig. 2), and four times higher than the emission from a GaAs–InAs–air structure to GaAs (curve 3 at $\theta > 90°$ in Fig. 2, emission to the air is negligible for the latter structure).

To evaluate the gain in the total terahertz power provided by the present scheme, we integrated (1) and corresponding angular power distributions for the reference structures over the solid angle 2π. The gain is $\sim 5 \times 10^3$ as compared to the emission from an air–InAs–Si structure to the air, $\sim 2 \times 10^2$ as compared to the emission from an air–InAs–Si structure to Si, and ∼50 as compared to the emission from a GaAs–InAs–air structure to GaAs.

To outcouple efficiently the generated terahertz radiation from the Si substrate into free space, we propose to use an extended hemispherical Si lens [17] cemented to the substrate (Fig. 1). In our design, the total thickness of the cylindrical extension and the substrate $\approx 0.27R$, with R the lens radius, is defined by the condition that the terahertz ray at maximum emission angle $\theta = 75°$ (Fig. 2) should be incident on the edge of the hemispherical lens [Fig. 3(a)]. The incidence angle for this ray, i.e., 15°, is near Brewster's angle, 16.4°, thus leading to efficient outcoupling [Fig. 3(b)]. The transmission angle is ≈62° and, therefore, the radiation emitted from the lens emerges with a divergence half-angle of ≈28° [Fig. 3(a)].

4 Conclusion

To conclude, we have proposed a structure to improve greatly the terahertz power generated at an optically excited surface of a semiconductor. The structure operates in the transmission geometry convenient for practical applications and, with InAs as an emitter, can provide a gain of $\sim 5 \times 10^3$ as compared to the terahertz emission from a bare surface of InAs and ∼50 as compared to the scheme with GaAs prism [6].

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