Strong interference enhancement of terahertz emission from a photoexcited semiconductor surface

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Abstract: To enhance terahertz emission from an optically excited semiconductor surface, we propose to sandwich a thin (as compared to the terahertz wavelength) semiconductor layer between a dielectric hyperhemispherical lens and metal substrate. The layer is excited through the lens. The substrate provides constructive interference of terahertz waves emitted to the lens directly from the layer and reflected by the substrate. The lens outcouples terahertz radiation into free space. For InAs layer sandwiched between MgO (or sapphire) lens and metal substrate, our theory predicts order of magnitude increase in the terahertz yield as compared to the previous schemes of terahertz emission from semiconductor surfaces.

OCIS codes: (260.7120) Ultrafast phenomena; (260.3090) Infrared, far; (230.7405) Wavelength conversion devices.

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1. Introduction

Excitation of semiconductor surfaces with above-bandgap femtosecond laser pulses is an established way to generate broadband terahertz radiation [1,2]. Due to simplicity and ability to operate with non-amplified lasers, this technique is widely used for time-domain spectroscopy and novel promising applications, such as detection of explosive and biological hazards [3], nondestructive inspection of pharmaceutical products [4], etc.

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 diffusion coefficients of electrons and holes, as in InAs (the photo-Dember effect [5]). In both mechanisms, the dipole is oriented perpendicularly to the surface, and such orientation creates the problem of extracting the radiation from a material (semiconductor) of high refractive index [6].

Several methods have been proposed to increase the extraction efficiency. One of them is imposing a large (of several tesla) magnetic field on the semiconductor surface. The field rotates the dipole from the surface normal, thus, increasing an overlap between the 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 for a 1 T magnetic field applied to InAs [9]. However, magnetic-field-enhanced emitters require large magnets; this limits the use of such emitters in many applications. Another method is redirecting the diffusion currents of photoexcited carriers along the excited surface. This can be achieved via creating a carrier gradient parallel to the surface by partially shadowing the excitation area [11] or using the InN films grown along the *a*-axis, in which carriers are accelerated by the in-plane intrinsic electric field [12].

A simple way to increase the extraction efficiency is putting a coupler (prism or lens) onto the semiconductor surface. Using, for example, 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 [13]. The radiated power, however, depends not only on matching the dielectric constants of the coupler and semiconductor but on the whole dielectric environment of the emitting dipole, i.e., on the thickness of the semiconductor layer and the dielectric constant of the substrate as well. For example, the structure in Ref [6]. with a thin (of ~500 nm thickness) InAs layer attached to a GaAs-prism coupler is far from optimal. As will be shown below, in such a structure the terahertz waves emitted to the GaAs prism directly from the InAs layer and after reflection from the InAs-air interface interfere destructively thus decreasing significantly terahertz yield. In the structure with a MgO lens attached to the surface of a thick (of ~500 µm thickness) InAs wafer [13], the direct and reflected from the InAs-air interface terahertz pulses arrive at the MgO lens with a delay, which exceeds the duration of the pulses. The pulses, therefore, do not interfere at all, and, thus, such potential enhancement mechanism as constructive interference is not exploited.

In this paper, we propose a structure that combines efficient outcoupling with optimal dielectric environment of the emitting dipole. The structure consists of a thin (as compared to the terahertz wavelength) semiconductor layer sandwiched between a dielectric hyperhemispherical lens and metal substrate. The latter can be considered as a perfect conductor in the terahertz range. Unlike the structures without a substrate [6,13], the terahertz waves reflected from the metal substrate undergo the 180° phase shift of the tangential to the substrate component of the electric field and, therefore, interfere constructively with the waves emitted to the lens directly from the semiconductor. This interference can enhance greatly terahertz yield. A small thickness of the semiconductor layer ensures independence of the interference conditions of the terahertz wave's wavelength and emission direction. The lens provides outcoupling and collimation of the terahertz radiation. Using an analytical

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formula for the angular distribution of the emitted terahertz power we compare the proposed structure with the reference structures [6,13] in favor of the former.

2. Geometry, model, and calculation

The geometry of the proposed structure and generation scheme are shown in Fig. 1. A thin layer ($0 < z < d$, d ~100-500 nm) of a semiconductor is placed on a metal substrate with a dielectric lens attached to the upper surface of the layer. The semiconductor is optically excited by a focused laser beam through the lens. The diameter of the focus spot on the semiconductor surface (a few tens of microns) is assumed to be much smaller than the terahertz wavelength. This ensures that the phased array effect [14] is negligible and the source of terahertz radiation can be modeled as a point dipole placed just below the semiconductor surface ($z = d$–) [15]. Noteworthy, considering the simple case of a point dipole is sufficient for reproducing the situation with a collimated pump laser beam [15]. We neglect a weak dispersion of the structure's materials 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 by a point monochromatic dipole from a grounded semiconductor layer covered with a dielectric half-space. The terahertz refractive indices of the semiconductor and dielectric are n_1 and n_2, respectively.

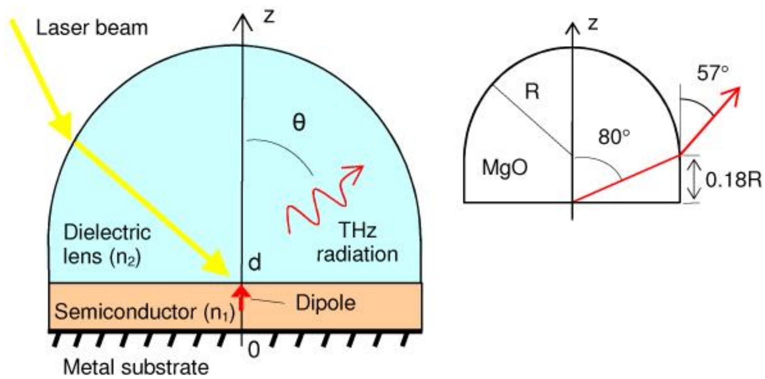

Fig. 1. Geometry of the structure and generation scheme. Inset: Design of the hyperhemispherical lens and ray-tracing diagram. The ray at maximum emission angle θ ≈80° is incident on the edge of the cylindrical extension and emerges at ≈57°.

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 [16]. Using this approach we obtain the time-averaged power radiated by the dipole to the dielectric within unit solid angle into direction θ,

$$P(\theta) = \frac{\omega^4 p^2 n_2^5 T_{21}^2 \sin^2\theta}{8\pi c^3 n_1^4} \left| \frac{1 + R_{13} e^{2i(\omega/c) n_1 d\cos\theta_0}}{1 + R_{13} R_{21} e^{2i(\omega/c) n_1 d \cos\theta_0}} \right|^2, \tag{1}$$

where $R_{21} = (n_1\cos\theta - n_2\cos\theta_0)/(n_1\cos\theta + n_2\cos\theta_0)$ and $T_{21} = 2n_1\cos\theta/(n_1\cos\theta + n_2\cos\theta_0)$ are the reflection and transmission coefficients (with respect to the magnetic field) on the dielectric-semiconductor boundary ($z = d$), respectively, $R_{13} = 1$ is the reflection coefficient (with respect to the magnetic field) on the semiconductor-metal boundary ($z = 0$), and θ_0 is the propagation angle of a terahertz wave in the semiconductor, $\cos\theta_0 = \sqrt{1-(n_2/n_1)^2\sin^2\theta}$.

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3. Results and discussion

Figure 2 shows $P(\theta)$ for the proposed structure with InAs as a semiconductor and MgO (or sapphire) as a material of the dielectric lens. We use n_1 = 3.8 for InAs and n_2 = 3.1 for MgO (sapphire). 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 Eq. (1) for all frequencies of interest $\omega/(2\pi) \le 3$ THz due to small d and, therefore, the normalized to maximum angular distribution $P(\theta)$ is practically independent of ω. The angular power distributions for the reference structures [6,13] are shown in Fig. 2 for comparison. These distributions are given by Eq. (1) but with other R_{13}. For the GaAs-InAs-air structure (an InAs layer attached to a GaAs prism) [6], $R_{13} = (\cos\theta_0 - n_1\cos\theta_{air})/(\cos\theta_0 + n_1\cos\theta_{air})$, where θ_{air} is the propagation angle in the air ($z < 0$), $\cos\theta_{air} = \sqrt{1-n_2^2\sin^2\theta}$. For the MgO-InAs-air structure (MgO lens attached to an InAs wafer) [13], we use $R_{13} = 0$. This corresponds to a typical experimental situation when the delayed (reflected from the InAs-air interface) terahertz pulse does not overlap with the pulse emitted directly to the lens and is eliminated by electro-optic sampling. The refractive index of GaAs at terahertz frequencies is n_2 = 3.6.

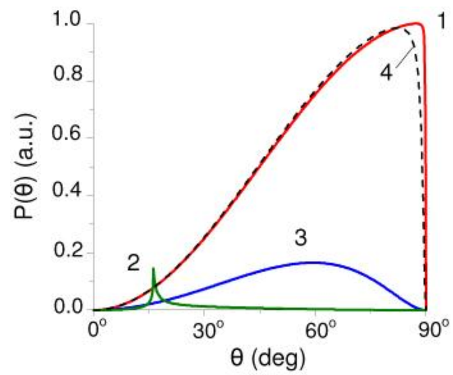

Fig. 2. Angular power distributions $P(\theta)$ for a MgO-InAs-metal structure with d = 500 nm (1), GaAs-InAs-air structure with d = 500 nm (2), and MgO-InAs-air structure with d = 500 µm (3). Curve 4 corresponds to approximate Eq. (2). The frequency is $\omega/(2\pi)$ = 1 THz. All curves are normalized to the maximum of $P(\theta)$ for the MgO-InAs-metal structure.

According to Fig. 2, the proposed MgO-InAs-metal structure provides a significant enhancement in the terahertz emission as compared to the structures in Refs [6,13]. The maximum of $P(\theta)$ for the MgO-InAs-metal structure (curve 1) is almost order of magnitude higher as compared to the emission from the GaAs-InAs-air structure to GaAs (curve 2) and from the MgO-InAs-air structure to MgO (curve 3), emission to the air is negligible for the two latter structures. Moreover, the distribution $P(\theta)$ is significantly broader for the MgO-InAs-metal structure (curve 1) than for the GaAs-InAs-air structure (curve 2). To evaluate the enhancement of the total terahertz power provided by the present scheme, we integrated the distributions $P(\theta)$ over the solid angle 2π. The enhancement is ~22 and ~7 as compared to the GaAs-InAs-air [6] and MgO-InAs-air [13] structures, respectively.

Mathematically, the strong emission enhancement in the MgO-InAs-metal structure with respect to the GaAs-InAs-air structure is related mainly to a large difference in the numerators in Eq. (1) for these structures. Indeed, for both these structures $\left|1+R_{13}e^{2i(\omega/c)n_1 d\cos\theta_0}\right|^2 \approx \left|1+R_{13}\right|^2$ due to a small thickness of the semiconductor layer, i.e., $2(\omega/c)n_1 d\cos\theta_0 \ll 1$. However, for the MgO-InAs-metal structure, R_{13} = 1 and, therefore, $\left|1+R_{13}\right|^2 \approx 4$, whereas for the GaAs-InAs-air structure, $\left|1+R_{13}\right|^2 \ll 1$ because of $R_{13} \approx -1$ for $\theta \ge 30°$, see Fig. 3(a) [for $\theta < 30°$, both curves are suppressed by the factor $\sin^2\theta$; a small peak in curve 2 at $\theta \approx 16°$ corresponds to the critical angle of total internal reflection ($\cos\theta_{air} = 0$), at

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which R_{13} = 1, Fig. 3(a)]. From the physical point of view, the enhancement is explained by different interference conditions in the structures. In the MgO-InAs-metal structure, the terahertz waves emitted to the coupler directly from the dipole and after reflection from the metal substrate interfere constructively due to the 180° phase shift of the tangential to the substrate component of the electric field in the reflected wave [Fig. 3(b)]. The phase shift results from the boundary condition of zero tangential electric field on the surface of a perfect conductor. In the GaAs-InAs-air structure, a phase shift close to 180° ($R_{13} \approx -1$ for $\theta \geq 30°$) is experienced by the magnetic field of the reflected wave and the normal, rather than tangential, component of its electric field [Fig. 3(c)]. Therefore, the direct and reflected waves interfere destructively [Fig. 3(c)].

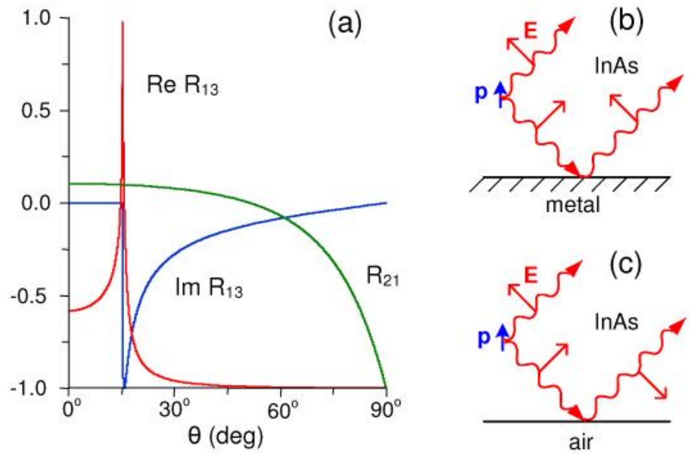

Fig. 3. (a) ReR_{13}, ImR_{13}, and R_{21} as functions of θ. (b,c) Direction of the electric field (**E**) in the terahertz waves emitted from the dipole and reflected from the metal substrate (b) and from the InAs-air boundary (c). The interference is constructive in (b) and destructive in (c).

In the MgO-InAs-air structure, due to large (~500 μm) thickness of InAs wafer the direct terahertz pulse and the one reflected from the InAs-air interface practically do not overlap in time – they arrive at the MgO lens with a delay of ~10 ps, which exceeds a ps-duration of the pulses – and, therefore, the pulses do not interfere. In a typical experimental situation the reflected pulse is eliminated by electro-optic sampling. Mathematically, the elimination corresponds to putting R_{13} = 0 in Eq. (1). Thus, the numerators in Eq. (1) for the MgO-InAs-metal and MgO-InAs-air structures differ by a factor of 4. According to Fig. 2, however, the maximums of curves 1 and 3 differ even more significantly – by a factor of ≈7 – and, furthermore, lie at different θ. To explain this, let us compare the denominators in Eq. (1) for the two structures. For the MgO-InAs-air structure (R_{13} = 0), $\left|1+R_{13}R_{21}e^{2i(\omega/c)n_1 d\cos\theta_0}\right|^2 = 1$. For the MgO-InAs-metal structure (R_{13} = 1), $\left|1+R_{13}R_{21}e^{2i(\omega/c)n_1 d\cos\theta_0}\right|^2 = \left|1+R_{21}e^{2i(\omega/c)n_1 d\cos\theta_0}\right|^2 \approx 1$ in a wide interval of θ not close to 90°, where $|R_{21}|$ is small due to proximity of n_1 and n_2 [Fig. 3(a)]. However, $R_{21} \to -1$ as θ approaches 90° [Fig. 3(a)]. This reduces significantly the denominator $\left|1+R_{21}e^{2i(\omega/c)n_1 d\cos\theta_0}\right|^2$ (note that $e^{2i(\omega/c)n_1 d\cos\theta_0} \approx 1$) and, therefore, emphasizes $P(\theta)$ near θ = 90° [the factor T_{21}^2 in Eq. (1) ensures $P(90°) = 0$]. From the physical point of view, the contribution of the denominator into the emission enhancement corresponds to the contribution of multiple reflections from the boundaries of the semiconductor layer. The waves emitted at angles not close to 90° escape the layer easily, whereas the waves at θ ≈90° experience significant reflection. As a result, the efficiency of pumping the terahertz field in the layer by the dipole increases for θ → 90°. Since, however, $T_{21}^2 \to 0$ at θ → 90° (the

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escape of the radiation from the layer is impeded for such θ) the maximum of the emitted power is achieved at an angle slightly shifted from 90°, i.e., at θ_{max} ≈84° (Fig. 2). In terms of reciprocity, the field excited in the layer by an incident wave at first increases with the incidence angle θ, attains a maximum, and then drops to zero at θ = 90°. For a MgO-InAs-metal structure with $2n_1\omega d/c \ll 1$, Eq. (1) can be simplified to the form

$$P(\theta) = \frac{\omega^4 p^2 n_2^5}{2\pi c^3 n_1^4} \frac{\sin^2\theta(\pi/2-\theta)^2}{(\pi/2-\theta)^2+\Delta^2} \tag{2}$$

with $\Delta = (\omega d/c)(1-n_2^2/n_1^2)n_2$. According to Eq. (2), $P(\theta)$ reaches a maximum $P_{max} \approx \omega^4 p^2 n_2^5 (2\pi c^3 n_1^4)^{-1}$ at $\theta_{max} \approx \pi/2-\sqrt{\Delta}$. For the parameters used above, Δ ≈0.01 and θ_{max} ≈84° which agrees well with the accurate result (curve 1 in Fig. 2). Accuracy of Eq. (2) is even higher for θ not close to 90° (compare curves 1 and 4 in Fig. 2).

4. Lens design

To outcouple the terahertz radiation into free space, we propose to use a hyperhemispherical MgO (sapphire) lens cemented to the InAs layer (Fig. 1). In our design, the thickness of the cylindrical extension of the lens is ≈0.18*R*, with *R* the lens radius. It is defined by the condition that the terahertz ray at close to maximum emission angle θ ≈80° (Fig. 2) should be incident on the edge of the extension (inset in Fig. 1). The incidence angle for this ray is ≈10° and, therefore, the radiation emerges from the lens with a divergence half-angle of ≈57° (inset in Fig. 1).

5. Conclusion

To conclude, we have proposed a structure to improve significantly the terahertz power generated at an optically excited surface of a semiconductor. In the structure, a thin (as compared to the terahertz wavelength) semiconductor layer is used rather than a thick wafer. The layer is placed on a metal substrate and covered with an outcoupler (lens). This scheme provides constructive interference of terahertz waves in a wide frequency range, thus, increasing significantly terahertz yield. For example, an InAs layer sandwiched between a MgO lens and metal substrate can provide a terahertz power enhancement of ~22 as compared to an ungrounded InAs layer attached to a GaAs prism [6] and ~7 as compared to an InAs wafer covered with a MgO lens [13].

The proposed method can be used to improve terahertz generation with collimated laser beams [15]. For this purpose, a grounded thin semiconductor layer should be covered with a prism rather than a lens as an outcoupler and the incidence angle of the laser beam is defined by the condition that the phased array effect should emphasize the emission in the maximum direction of $P(\theta)$ for a point dipole.

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