Terahertz emission from black silicon

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We report on a terahertz emitter made out of black silicon. The black surface structure absorbs the whole optical pump power in the very surface. In contrast to expectations for indirect semiconductors, the black structure shows an emission in the terahertz range. The emitted radiation of the black silicon crystal is characterized for different parameters using terahertz time-domain spectroscopy. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2978096]

The electromagnetic regime between the infrared and microwave radiation has become accessible over the past decade due to a combination of advanced laser sources and highly sophisticated electronics. A number of different methods for the generation of terahertz radiation have been developed including pure optical, optoelectronic, and pure electronic devices. Optical sources typically apply femtosecond lasers to generate light-induced polarization changes by excitation of charge carriers above the band gap. With these sources, a broadband emission for spectroscopic measurements between 100 GHz and 4 THz is obtained.[1] For this purpose semiconductors with high absorption in the near infrared (NIR), high electron mobilities, fast recombination rates, and short carrier lifetimes are used as target material. For these so-called photoconductive terahertz emitters and detectors, radiation-damaged silicon on sapphire or (low-temperature grown) gallium arsenide[2] is widely used. Other semiconductors such as doped indium arsenide, indium nitride, or indium phosphide are well suited materials for surface terahertz emitters. Here, the surface depletion field due to Fermi level pinning and the photo-Dember-effect[3] lead to strong emission of terahertz radiation after generation of photocarriers in the depletion layer of the semiconductor material.

So far silicon has only rarely been used as a material for terahertz emitters. Because of its small absorption coefficient and low dispersion[4] together with a high-refractive index in the terahertz range ($n_{Si}^{THz}=3.4$), high resistivity silicon is often used as a beam splitter for terahertz radiation or as a high-refractive lens material attached to a photoconductive switch. Scattering losses can be minimized by using surfaces with a roughness lower than the wavelength of terahertz radiation. A further advantage of terahertz optics made out of silicon is that the copropagating infrared radiation is absorbed sufficiently.

In this letter we present a study of black silicon (BS) as an emitter of terahertz radiation. BS has the advantage of an extremely high absorption throughout the visible and infrared spectral regions. Due to the black structure (Fig. 1), the large penetration depth of silicon being an indirect semiconductor is effectively reduced to a submicron range under the surface, independent of the "path" of the absorbed photons (Fig. 2). Multiple reflections lead to an absorption in nanoscopic needles where the confinement of the electron-hole pair should result in large changes of the local potential. The needles are interconnected only via the bulk material at their back end. Therefore BS shows an anisotropy toward the surface which might be used as a polarization effect to generate terahertz emission.

The BS is a ⟨1 0 0⟩ oriented unintentionally phosphor doped silicon wafer with a conductivity of 2–10 Ω cm. The

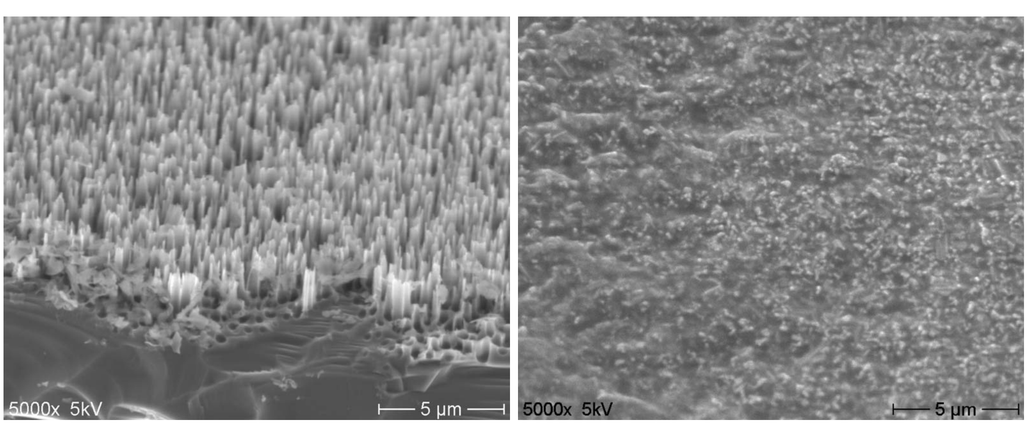

FIG. 1. BS sample imaged with a scanning electron microscope. Left: black silicon: right: damaged sample.

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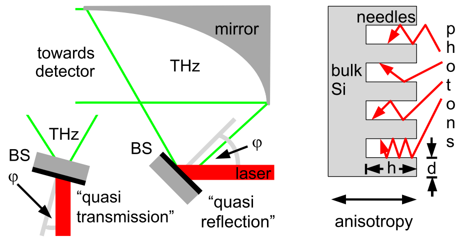

FIG. 2. (Color online) Experimental setup. Left: BS emitter in quasitransmission; middle: quasireflection geometry; right: possible photon paths.

thickness of the sample is 525 μm. The BS layer was prepared on the cleaned wafers in an inductively coupled plasma via reactive ion etching (SI-500-C, Sentech Instruments Berlin) for 10 min using sulfur hexafluoride and oxygen.[5] The surfaces are characterized by scanning electron microscopy under 45° observation (Fig. 1). The measured dimensions of the needles are d=300 nm in diameter and h=2 μm in height, varying statistically.

The basic experimental setup is shown in Fig. 2. The terahertz time-domain spectroscopy system consists of a Ti:sapphire pump laser at 780 nm center wavelength, 100 fs pulse duration, and 2.5 W average power. The electric field of the terahertz wave is detected with a low temperature grown gallium arsenide antenna with 20 μm dipole length. The emitters under investigation are measured in a quasioptical reflection geometry, corresponding to 90° between the pump laser and direction of detection. In addition the emitters were also tested in a quasitransmission geometry to detect the oscillation axis of the terahertz emitter in a reproducible grazing incidence configuration. Here $\varphi=0^\circ$ corresponds to incidence normal to the BS wafer, while $\varphi=\pm 90^\circ$ is a grazing incidence configuration. To prevent thermal influences on the measured signals or even damage of the samples, the emitters are mounted on a heat sink. The laser beam is not focused and has a diameter of 750 μm.

When irradiated with ultrashort pulses from the Ti:sapphire laser, terahertz emission was observed from the BS emitter. To make sure that the terahertz generation is really caused by the surface properties of the silicon sample, the black surface was mechanically damaged. Thereby the structure of the tiny needles was destroyed and the anisotropy toward the surface was canceled. A considerable reduction of terahertz amplitude was measured (Fig. 3). The emission from the damaged surface of the BS is comparable to terahertz emission from a regular unpolished silicon wafer without any surface treatment. The black surface obviously gives rise to an additional polarization in the terahertz range. Low residual emission is observed also from the sawed unprocessed surface. On the other hand, a polished silicon wafer did not show any detectable terahertz emission.

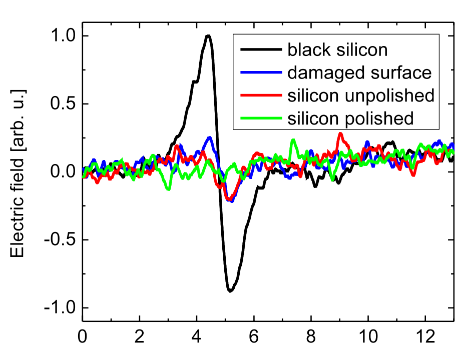

FIG. 3. (Color online) Terahertz electric field for different surface qualities: black, damaged, unpolished (sawed), and polished.

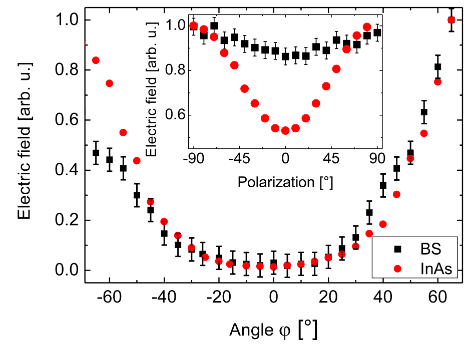

FIG. 4. (Color online) Angle dependent terahertz emission in quasitransmission geometry. Inset: terahertz output of BS and InAs for different pump polarizations, both plots normalized.

In order to determine the direction of the oscillating dipoles, a measurement in quasitransmission was performed (Fig. 4). In this case the black surface faces the laser while the terahertz optics images the backside of the BS emitter onto the detector. The maximum of the terahertz emission was observed close to grazing incidence (around $\varphi=\pm 70^\circ$), whereas no emission was detected for a perpendicular illumination ($\varphi=0^\circ$).

The inset of Fig. 4 shows the dependence of terahertz emission from a BS emitter on the incoming beam polarization. Taking into account the error bars for the measurement, the output of BS is roughly independent of the pump beam polarization. The behavior of p-doped indium arsenide is added for comparison. Both plots are normalized to 1, despite the approximately 50 times higher output of the InAs emitter.

In order to determine the angular emission characteristics of the BS surface emitter, the electric field of the generated terahertz radiation was measured in quasireflection geometry as a function of rotation angle φ. A clear maximum around $\varphi=45^\circ$ was observed, which corresponds to the specular reflection of the pump beam comparable to unstructured surface emitters. The theoretical curve shows the emission characteristics of a diffraction limited terahertz source calculated with a pump beam diameter of 1060 μm and a terahertz wavelength of 600 μm. In this plot the integration over a solid angle of $\pm 15^\circ$, the viewing angle of the mirror, is also included.

Indirect semiconductors are not widely used as terahertz emitters because they only show very weak terahertz emission compared to other available sources. According to Zhang and Auston[6] this fact is caused by the large absorption length of photons in the surface. As a consequence, the region of the generated free carriers and the acceleration by the surface field do not overlap sufficiently. In order to use an indirect semiconductor such as silicon as a terahertz emitter with optical excitation, it is important to reduce the penetration depth considerably. In the case of BS this is accomplished by multiple reflections within the surface structure (Fig. 2).

In this letter we show that terahertz emission in silicon under optical excitation is strongly influenced by the surface

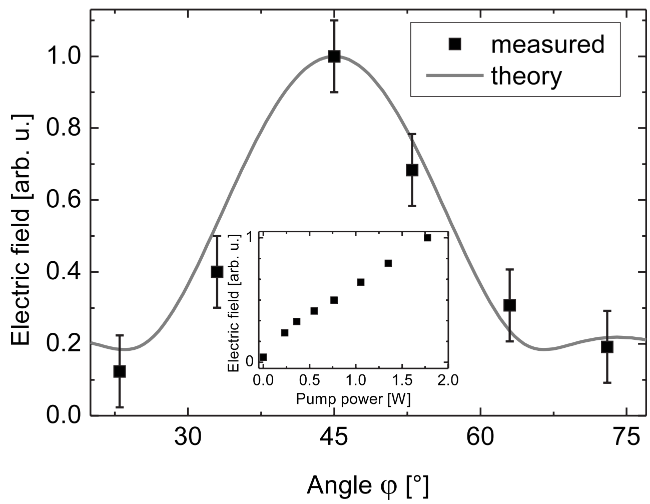

FIG. 5. Terahertz output of BS for different angles φ in quasireflection. Inset: pump power dependence of the terahertz emission.

structure. The orientation axis of the oscillating Hertzian dipole is not perpendicular to the surface of the individual needles (in plain) but normal to the BS wafer. The emission characteristic in terms of dependence on the pump laser power and emission direction is comparable to the emission of InAs.[7,8] The latter one shows a strong surface field due to Fermi level pinning. So the free charge carriers are accelerated in the intrinsic field of the semiconductor.

In contrast to the setup for terahertz generation, used by Mu *et al.*,[9] who illuminated a 340 nm layer of Si on SiO_2 as surface emitter, in our setup the dipoles oscillate out of plain. The photo Dember-effect has to be taken into account also for our sample since the different diffusion coefficients for electrons and holes are inherent to silicon. The required structural asymmetry[10] is provided by the needles.

The terahertz amplitude is almost insensitive to the polarization of the pump radiation. For InAs this is important because the Fresnel reflection at the surface is polarization dependent. This reduces the effectively absorbed laser power. In the case of BS nearly all the pump power is absorbed independent of the polarization.

Figure 5 shows that the emission cone follows the restrictions of Huygens law since the emission is observed only in the direction of the reflected incident light (quasioptical reflection). The refractive index of air is nearly the same for the NIR and terahertz ranges ($n_{\text{air}}^{\text{THz}} \approx n_{\text{air}}^{\text{NIR}}$). So the phase fronts of the fundamental dipoles interfere constructively in the same direction like for the NIR waves. The subwavelength structure of the needles has no influence on the terahertz beam properties such as divergency and beam diameter.

As the terahertz pulse length was in the range of 1 ps, no broadband terahertz spectrum was observed. In semiconductors the penetration depth of NIR photons and the carrier lifetime are strongly dependent on the dopant concentration. An optimization of this parameter will increase the terahertz output and spectral width of the BS emitter.

Also for other direct semiconductor emitters, surface treatment can bring useful advantages: The absorbed laser power is increased, which scales linearly with the terahertz electric field. Also there will be no need for a beam dump such as a Teflon disk to absorb the reflected part of the laser power, which otherwise could damage other optical components or would increase the noise of the TDS system. As a consequence this reason for additional losses (typically 20%) in the terahertz beam path can be removed.

The presented results demonstrate that in BS the space charge layer and the penetration depth can be designed to be within the same range. Photoinduced carrier separation in the region of the space charge layer is usually faster and less dependent on material defects, so lower grade material might be used if nanostructured surfaces similar to BS are applied. Furthermore, the orientation of the dipole perpendicular to the surface induces an electron movement in the same direction. This effect could be used for solar cell devices by using economic low grade *p*-doped BS in a heterojunction device with, e.g., a transparent semiconducting window material.[11,12] Whether the observed dipole perpendicular to the space charge layer might be used for photovoltaic applications will have to be shown separately.

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