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Comparison of photoexcited *p*-InAs THz radiation source with conventional thermal radiation sources

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P-type InAs excited by ultrashort optical pulses has been shown to be a strong emitter of terahertz radiation. In a direct comparison between a *p*-InAs emitter and conventional thermal radiation sources, we demonstrate that under typical excitation conditions *p*-InAs produces more radiation below 1.2 THz than a globar. By treating the globar as a blackbody emitter we calibrate a silicon bolometer which is used to determine the power of the *p*-InAs emitter. The emitted terahertz power was found to be 98 ± 10 nW in this experiment. © *2009 American Institute of Physics*.

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I. INTRODUCTION

Conventional sources of radiation in the terahertz or the far-infrared regime include thermal blackbody radiators, where one of the most common is the globar. The globar is a rod of synthetic silicon carbide (SiC, carborundum) commonly manufactured to be about half a centimeter in diameter and a few centimeters in length, through which a current of typically 4 A is allowed to pass, causing it to heat up and glow.

In the past several decades, with the advent of ultrashort pulsed laser technology, a range of photoexcited terahertz sources has been developed. In one typical technique, terahertz radiation is generated via a surface current transient (surface depletion field plus photo-Dember effect) or the optical rectification effect by illuminating semiconductor surfaces with ultrashort (<100 fs) pulses of near-infrared (NIR) radiation.[1–4] This technique allows terahertz time-domain spectroscopy via a pump-probe arrangement with the technologically desirable features of phase-coherent detection, high signal-to-noise ratios, and room-temperature operation. However, until now the radiation characteristics (the absolute power or the spectral bandwidth) of the signals generated by ultrashort pulses have not been compared to that of conventional thermal sources. We directly compare the power spectra of one common photoexcited surface emitter *p*-type InAs, which is one of the best surface emitters[5] with that from a conventional globar and a mercury (Hg) lamp.

We note that a common difficulty for researchers working in the terahertz regime is the lack of accurate methods to determine the average absolute power of terahertz emitters. Most articles in the literature report the generated power as a comparison to other common terahertz emitters. Here, by utilizing the well know emission characteristics of a globar that is commonly approximated to be a good blackbody source, we establish a power calibration factor for a silicon bolometric detector and use it to evaluate the average absolute output power from a *p*-InAs emitter.

II. EXPERIMENT

We performed the power calibration on a liquid-helium-cooled (4.2 K) silicon bolometer from Infrared Laboratories (IRL) in USA. The detection system (along with the photoexcited emitter) shown in Fig. 1 consisted of a 1 mm thick polystyrene sheet and a 1 mm thick silicon plate at the entrance aperture. These were used to remove background optical noise by filtering out any remnant NIR radiation and to protect the sensitive detector element from damage. Lock-in detection was used while mechanically chopping the NIR beam at a frequency of 183 Hz to remove background thermal noise.

The reference source used for the bolometer calibration was an I-series Globar manufactured by Surface Igniter Corporation in USA. As shown in Fig. 2, the globar is a cylindrical rod with a reduced mass spiral element that glows when a sufficiently large current is made to pass through it. A current of 3.80 A at a supply voltage of 22.0 V was used for

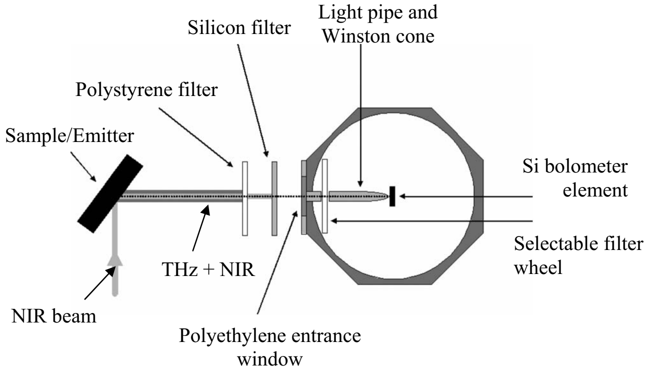

FIG. 1. Bolometric detector and filter arrangement used for the power calibration measurements.

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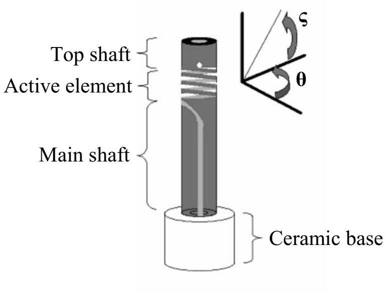

FIG. 2. Diagram of the globar showing the components and the active region.

most of the measurements. By varying the current supplied to the globar, the total emitted power and the peak temperature of the globar could be easily controlled. We resorted to using a globar in this work as it is known to approximate a blackbody radiator and also produces a stable output.

The investigated photoexcited emitter was a (100)-oriented *p*-type (Zn-doped) InAs wafer having a carrier concentration of $(0.93-2.1)\times 10^{16}\ \text{cm}^{-3}$ at 77 K as specified by the manufacturer. This wafer was illuminated by a 12 fs NIR pulse train at a repetition rate of 75 MHz with an average power of 300 mW produced by a mode-locked Ti:sapphire laser (Femtosource Compact[6]). The NIR radiation was centered at a wavelength of 790 nm with a full width at half maximum spectral width of about 100 nm. A 20 cm focal length lens was used to focus the incident radiation onto the wafer.

As shown in Fig. 1, the InAs wafer was excited in a "reflection" geometry and the generated terahertz radiation was detected in the specular direction. The generated terahertz power was dependent on the incident angle and the power was found to be a maximum at the Brewster angle (~75°). Since the Brewster-angle geometry was not always very convenient in practice, an incidence angle of 45° was also employed. This 45° configuration resulted in a 5% decrease in the signal strength compared to the optimum Brewster-angle geometry.

We also used a Bomem DA3 rapid-scan Fourier-transform spectrometer (FTS) to obtain and compare the power spectra of the InAs emitter and the globar, as well as a Hg lamp. The detector used in conjunction with the FTS was another IRL silicon bolometer with specifications and performance similar to the one used earlier.

III. POWER CALIBRATION

The calibration of the bolometer was achieved by comparing the experimentally detected signal with the theoretically determined power using a globar as the reference source. By approximating the behavior of the globar to a blackbody radiator, we can derive the spectral radiance using Planck's law of blackbody radiation[7] expressed as

$$I(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}, \tag{1}$$

where I is the spectral radiance, ν is the frequency, k is the Boltzmann constant, h is the Planck constant, c is the speed of light, and T is the absolute temperature. By integrating the spectral radiance over the actual frequency spectrum, we can obtain the total radiance. Then, by comparing this radiance value to the measured bolometer signal, we can effectively determine a "calibration factor" for the complete detection system. The calibration factor C measured in units of watt/millivolt would be given by

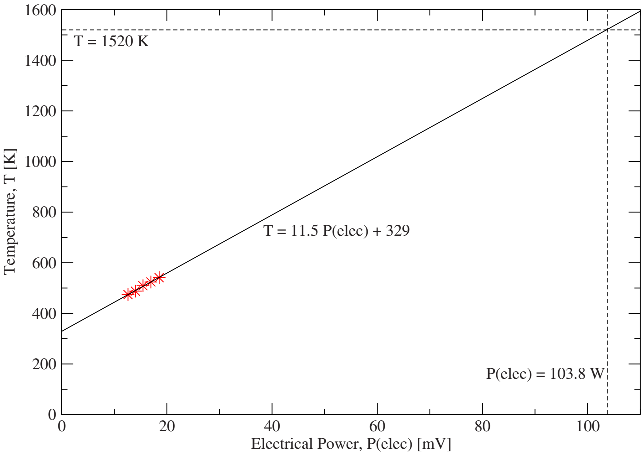

FIG. 3. (Color online) Globar temperature as a function of the electrical power measured using an IR thermometer (crosses) with temperature extrapolation (solid line).

$$C=\frac{\Phi}{S_{\text{meas}}}=\frac{L\Omega A}{S_{\text{meas}}}. \tag{2}$$

Here Φ is the radiant flux, L is the radiance, Ω is the solid angle of emission, A is the area of the emitting surface, and S_{meas} is the measured bolometer signal.

IV. RESULTS

The temperature of the globar was determined using an infrared thermometer (Fluke 61) having a measurable upper limit of 260 °C. Since this upper limit was much lower than the actual operating temperature, we resorted to an extrapolation technique to circumvent this problem. The globar temperature was varied within the measurable range of the thermometer by controlling the electrical power input to obtain the characteristic temperature dependence of the globar with electrical power. This dependence, shown in Fig. 3, was then extrapolated to figure out the actual operating temperature, which was found to be 1520 ± 70 K. As expected, the temperature variation with electrical power resulted in a linear dependence validating the extrapolation.[8]

Although the globar is generally treated as a perfect blackbody radiator, this is not really the case. It is in fact a "grey-body" radiator, and as such will have a temperature-dependent emissivity (denoted as ε) that is less than one. The emissivity of a similar globar at a peak temperature of 1530 K as measured by Ukhanov and Filippov[9] was found to vary between 0.75 and 0.95. Therefore, we used the average value of 0.85 as a reasonable value for the emissivity in our case.

In order to take into account the nonideal response introduced by the filters in the experimental setup when determining the frequency range and any other affects such as due to water vapor absorption, a filter correction factor (CF) was

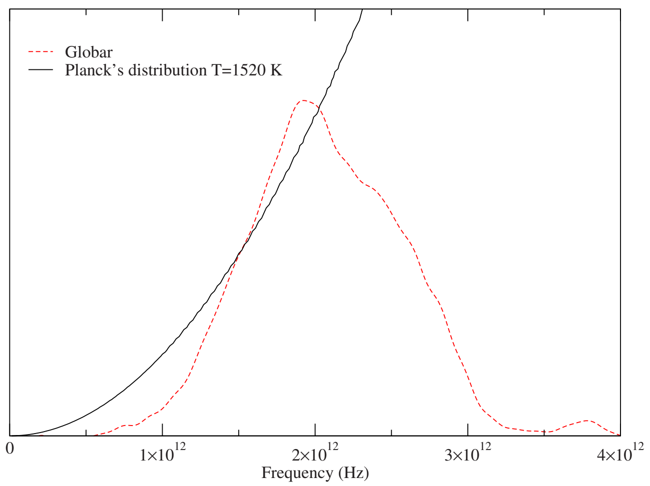

FIG. 4. (Color online) Comparison of globar spectrum (dashed curve) measured using the FTS compared to the theoretical Planck's distribution (solid curve). This figure was used to determine the CF associated with the fall off of the signal toward the higher frequency cutoff.

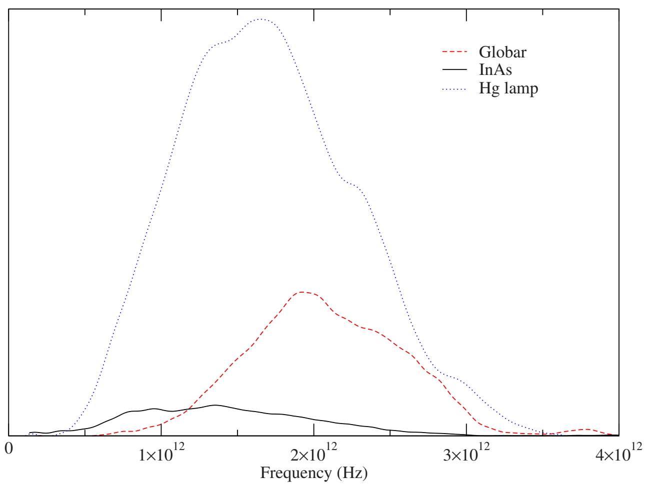

FIG. 5. (Color online) Comparison power spectra of *p*-InAs (solid curve), globar (dashed curve), and Hg lamp (dotted curve) as measured using the FTS.

applied to the theoretical radiance. This CF was estimated by comparing the Planck's distribution with the measured spectrum of the globar using the FTS, as shown in Fig. 4. By doing so, we eliminated the need for a complex investigation of the filter characteristics. Provided that the filters used in the system do not limit the maximum detection range, their characteristics would be accounted for in the CF. The estimated CF was found to be 0.387 ± 0.005.

After correcting for the nonideal response, a more realistic expression for the radiance can be written as

$$L = \varepsilon \times \mathrm{CF} \times \int I(\nu,T)\,\partial\nu. \tag{3}$$

This expression was used to determine the total radiance by numerically integrating $I(\upsilon,T)$ taken from Eq. (1). The limits of integration were taken to be from 0 to 3.4778 THz, where the upper limit was the maximum detectable frequency of our detection system governed by the filters. With the above emissivity and filter correction values applied, the total radiance was determined to be $1.95 \pm 0.22\ \mathrm{W/sr\ m^2}$.

In order to derive the calibration factor C based on Eq. (2), we calculated the effective area (A) of the emitting surface using the actual dimensions of the globar taking into account the contributions from both the inner and outer surfaces of the active element. The solid angle (Ω) was initially evaluated by considering the globar as an isotropic point source and using the dimensions of the bolometer entrance aperture. However, a measurement in the vertical plane (about the angle ς shown in Fig. 2) showed that the emission was not isotropic. The emission is uniform in the azimuthally horizontal plane around the active element but reduces as ς approaches ±90° toward the ends of the shaft. Therefore, a weighting factor was applied to the final solid angle calculation to account for the larger proportion of emission around the active element $(-40° \leq \varsigma \leq 40°)$. Then, based on Eq. (2), the calibration factor C for this specific detection system was evaluated to be $0.30 \pm 0.02\ \mathrm{nW/mV}$ for a bolometer gain of 1000 and a chop frequency of 171 Hz. With this value of C, the maximum average absolute power achieved from the photoexcited InAs emitter (at 45° incidence and 300 mW of optical power) was found to be $98 \pm 10\ \mathrm{nW}$. Based on past experience in using a similar IRL bolometer side by side with a calibrated bolometer from QMC Instruments in U.K. for estimating terahertz power,[10] an independent estimate revealed an upper limit of 100 nW for the average absolute power, which is consistent with the above calculated value.

We also measured the power spectra of the globar, the InAs emitter, and also a Hg lamp using the FTS under similar experimental (detection) conditions with typical input conditions for the globar and the Hg lamp and the same input excitation conditions as used before for the InAs emitter. These spectra are plotted in Fig. 5 and indicate a surprising feature where the output power from the InAs emitter exceeds that of the globar for frequencies below ~1.2 THz. This is an unexpected result since conventional thermal sources are known to radiate considerably high broadband power. It has been demonstrated that photoexcited InAs can radiate more low terahertz frequency content than the commonly used globar. Furthermore, for the Hg lamp, as expected, we see a considerably high spectral content over a broad terahertz frequency range, although closer investigation reveals that InAs radiates slightly more power for frequencies below about 0.4 THz.

V. CONCLUSION

We describe a technique to determine the average absolute power of photoexcited terahertz emitters by using a conventional globar to calibrate an IRL bolometer. This technique was used to determine the average absolute power of a *p*-InAs emitter found to be $98 \pm 10\ \mathrm{nW}$, which is consistent with independent estimates. By comparing the terahertz radiation spectra of thermal sources versus the InAs emitter, we discover a previously unknown advantage of the photoexcited emitter where more low frequency contents are readily achievable in addition to the already known advantages of phase-coherent detection, room-temperature operation, and reduced thermal background.

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