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Measurements of Thermal Emission from Silicon Wafers highlighting discrepancies with Planck's Law at sub-THz frequencies

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Abstract—The thermal energy radiated by silicon wafers with different conductivities is characterized experimentally in the mm and sub-mm wave ranges. These samples are heated up, and the energy that they radiate thermally is captured by different horn antennas covering the frequency band between 75 and 500 GHz. The energy radiated (in the order of pW) and collected by the horn antennas is subsequently detected by zero bias Schottky diodes. The measured thermal radiated power agrees with the prediction from Planck's law for the highly doped wafers, corresponding to high conductivities. However, for low conductivities, the measurements show a descending pattern as a function of the frequency, which is not in line with expectations from Planck's law. Parallely, we have developed a theoretical model providing a classical explanation of these results [1].

I. INTRODUCTION

According to radiometry, [2][3][4][5] the energy radiated by a body at given temperature T , and at a frequency f , in thermodynamic equilibrium, equally radiates and absorbs a specific power spectrum of electromagnetic (EM) radiation given by:

$$B(f, T) = e_{mi}(f, T) \cdot B_{bb}(f, T) \quad (1a)$$

$$B_{bb}(f, T) = \frac{8}{\lambda^2} \cdot \frac{h \cdot f}{e^{h \cdot f / k_B T} - 1} \quad (1b)$$

The brightness $B(f, T)$ is expressed in terms of Planck's Black Body radiation law, $B_{bb}(f, T)$, and proportional to the emissivity, $e_{mi}(f, T)$, a purely electromagnetic quantity. For frequencies $hf \ll k_B T$ ($h \approx 6.6 \cdot 10^{-34} \text{ J s}$ is the Planck's constant and $k_B \approx 1.38 \cdot 10^{-23} \text{ J/K}$ is Boltzmann constant), Planck's law is approximated by the simpler Rayleigh-Jeans law, according to eq. 5 of [3] this gives $B_{bb}(f, T) \approx 2 \frac{k_B T}{\lambda_0^2} e_{mi}(f, T)$. Where λ_0 indicates the free space wavelength.

It is impossible to underestimate the role of Planck's law in modern physics. Nevertheless, the experimental validation of Planck's law, after an exhaustive literature review, seems to be not complete. Crovini and Galgani [6] in 1984, pointed out that the experiments attempting a rigorous validation with known sources in the infrared and visible range date back to 1921, see [7]. On the other end, the Cosmic Microwave Background radiation measurements, by Mather et al. in 1994, [8], dealt with remote sources with unknown characteristics including for their emissivity.

For silicon, to our knowledge, the only experimental validation where the brightness in the Rayleigh-Jeans limit was measured, has been conducted by Sato *et al.* [9] in 1967. Ravindra *et al.* [10] obtained a qualitative fit of the data from Sato using eq. (1) in the Rayleigh-Jeans limit for measurements corresponding to high conductivities in 2001. However, no measurements have been ever reported for low conductivity semiconductors, and in the sub-THz spectrum.

In this contribution, we present experiments that quantify the energy radiated in the sub-THz spectrum by crystalline silicon wafers, one of the semiconductors most widely used in the microelectronics industry.

II. EXPERIMENTAL SETUP

Two different N-type (phosphorus doped), <100> orientation, CZ silicon wafers with thicknesses w_z ranging from $300 \mu\text{m}$ to $600 \mu\text{m}$ and diameters $D_w = 10 \text{ cm}$ are used as thermal radiation sources. The main difference between these two wafers is their conductivity, one with high conductivity ($0.001 - 0.005 \text{ Ohm cm}$) and the other one with low conductivity ($0.1 - 1 \text{ Ohm cm}$).

The radiation emerging from the wafers is collected via directive, singly polarized horn antennas coupled to a Zero Bias Detector (ZBD) placed in front of the wafers at roughly 10 cm of distance. This can be seen in Fig. 1 where a sketch together with a picture of the setup is presented. We investigate the radiation coming from the wafers in a frequency range from 75 to 500 GHz, using four different horn antennas since each of the horns have a limited frequency bandwidth. We use a zero bias Schottky detectors from Virginia Diodes (VDI) [11] directly connected to the horn antenna as the receiver. The detectors take advantage of the low noise properties of Schottky barrier diodes [12], and are hosted in rectangular waveguide cavities that are directly connected to corresponding horns. The ZBDs are selected such that their frequency band matches the one of the horn antennas.

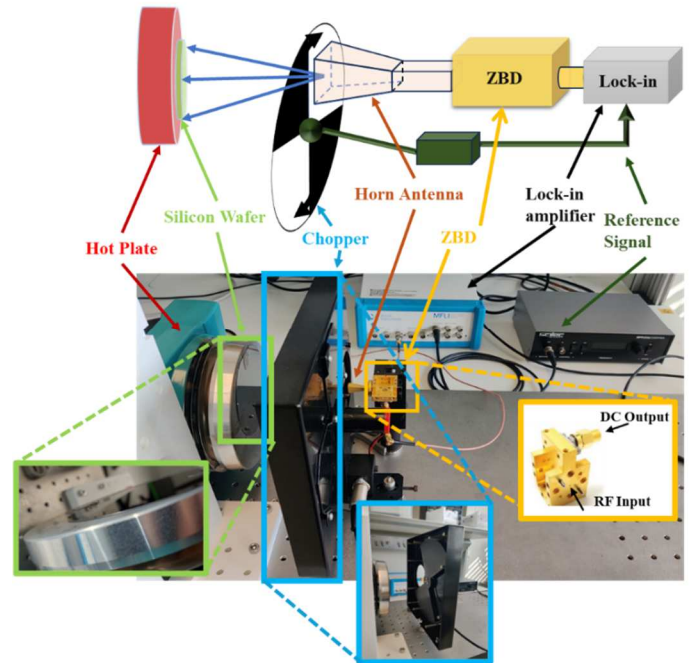


Fig.1 Sketch of the measurement setup including the silicon wafer, the hot plate, the chopper, the horn antenna, the ZBD and the lock-in amplifier.

III. RESULTS

We start with the high conductivity one, which has a nominal resistivity indicated by the provider in the range $\rho \in (1 \rightarrow 5) 10^{-5} \Omega - m$ (or $n \in (8 \rightarrow 1) 10^{25} \text{el}/m^3$). With a thickness of $525 \mu m$. The wafer was heated to 475 K . The actual value of the best fitting trial doping, $n_{\text{trial}} = 0.65 10^{25}$, is slightly outside the range indicated by the provider. However, considering that the levels of power received are at the limits of the sensitivity of the detectors, the frequency dependence of the calculation and the measurements, see Fig. 2, is extremely good. For this sample, a growing spectral energy as a function of the frequency is predicted also by the companion work in [1].

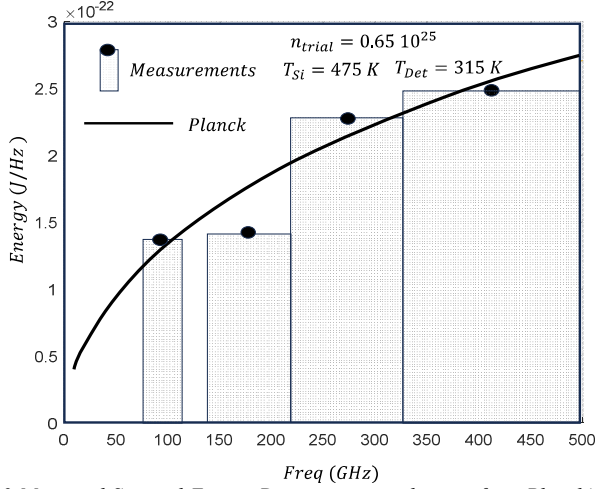


Fig.2 Measured Spectral Energy Densities vs. predictions from Planck's law corrected with estimated emissivity for the estimated phosphorus doping of $n = 0.65 10^{25}$. Temperature of the silicon $T_{\text{si}} = 475 \text{ K}$ and temperature of the detector $T_{\text{det}} = 315 \text{ K}$.

The story is completely different for lower doping corresponding to lower conductivity. The measured spectral energy is presented in Fig. 3.

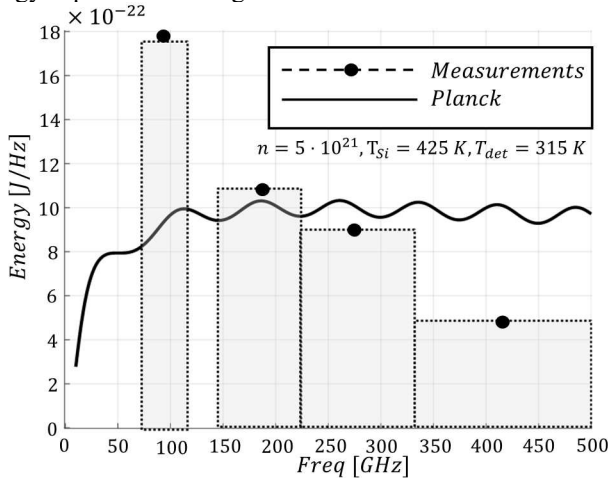


Fig.3 Measured Spectral Energy Densities vs. predictions from Planck's law corrected with estimated emissivity for the estimated phosphorus doping of $n = 5 10^{21}$. Temperature of the silicon $T_{\text{si}} = 425 \text{ K}$ and temperature of the detector $T_{\text{det}} = 315 \text{ K}$.

In Fig. 3 Planck's prediction is compared with the measurement done when the hot plate was set to $T_{\text{si}} = 425 \text{ K}$. The simulated curves correspond to a trial doping taken to be $n = 5 10^{21}$, estimated from time-domain spectroscopy measurements, while the thickness of the sample was $600 \mu m$. However, it is

evident that no choice of doping or thickness would ensure that the frequency dependence of the estimated spectral energy would match the frequency decreasing behavior of the measurements. It should be noted that for the low conductivity the measured energies are much higher, and thus the results more accurate, than for the high conductivity case.

IV. CONCLUSIONS

A series of measurements were performed to quantify the thermal radiation from n doped silicon wafers. When the doping of the wafer corresponds to high conductivity, the received energy is small because of the high reflectivity of the wafer and presents a small growth as a function of the frequency. A credible trial doping value can be identified so that Planck's law, mediated by the emissivity, is in good agreement with the measurements. However, for lower doping and corresponding lower conductivities, when the energy received is much higher, the measurements strongly disagree with the predictions of Planck's law for any trial doping. The radiation intensity is clearly diminishing as a function of the frequency for all temperatures.

While we hope for confirmations from other researchers, we are also very confident on the results shown in this experimental paper. The reason is that, before these measurements were made, one of these authors developed a classic theory for thermal radiation from ohmic media, [1], that explains the frequency dependence of the measured results for both the high and low conductivities presented here.

REFERENCES

- [1] Andrea Neto, "The THz Catastrophe. Part 2: the EM Degrees of Freedom due to Thermal Agitation", TechRxiv. June 03, 2024. DOI: 10.36227/techrxiv.171742492.23095864/v1
- [2] Planck, "The Theory of Heat Radiation" (1906)
- [3] G. Bekefi, and Sanborn C. Brown "Emission of Radio-Frequency Waves from Plasmas" American Journal of Physics 29, 404 (1961);
- [4] Fawwaz T. Ulaby, Richard K. Moore, Adrian K. Fung, "Microwave remote sensing: active and passive volume 1: microwave remote sensing fundamentals and radiometry"; The Artech House Remote Sensing Library
- [5] S. van Berkel, O. Yurduseven, A. Freni, A. Neto and N. Llombart, "THz Imaging Using Uncooled Wideband Direct Detection Focal Plane Arrays," in IEEE Transactions on Terahertz Science and Technology, vol. 7, no. 5, pp. 481-492, Sept. 2017, doi: 10.1109/TTHZ.2017.2736338
- [6] L. Crovini, L. Galgani "On the Accuracy of the Experimental Proof of Planck's Radiation Law"; Letere al Nuovo Cimento Vol. 39, No. 10, 10 Marzo 1984;
- [7] Rubens H and Michel G 1921 Prufung der Planckschen Strahlung Strahlungsformel Z. Phys. 22 569
- [8] Mather, John C., et al. "Measurement of the cosmic microwave background spectrum by the COBE FIRAS instrument." The Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 420, no. 2, p. 439-444 420 (1994): 439-444.
- [9] Tsutomu Satō "Spectral Emissivity of Silicon", Japanese Journal of Applied Physics, Volume 6, Number 3, 19967
- [10] N.M.Ravindra, et al. "Emissivity Measurements and Modeling of Silicon-Related Materials: An Overview" International Journal of Thermophysics, Vol. 22, No. 5, September 2001
- [11] Virginia Diodes- ZBD, <https://www.vadiodes.com/en/products/detectors>
- [12] J. L. Hesler and T. W. Crowe, "NEP and responsivity of THz zero-bias Schottky diode detectors," 2007 Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz Electronics, Cardiff, UK, 2007, pp. 844-845, doi: 10.1109/ICIMW.2007.4516758.