# Optical Performance of Liquid Nitrogen Cooled Transistor-Based THz Detectors

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***Abstract*— We report on the improvement of the optical performance of THz detectors based on antenna-integrated 90nm Si CMOS field-effect transistors (TeraFETs) when cooled with liquid-nitrogen (temperature range 77-297 K). The minimum optical noise-equivalent power (NEP) at 77 K is as low as 11.7 pW/√Hz at 0.6 THz, which corresponds to a decrease by a factor of 3.8 compared to room temperature, and approaches the optical sensitivity levels of commercial helium-cooled bolometers. The channel static resistance, its optical responsivity and NEP measurements reveal a specific feature for this family of detectors: that there are gate bias regimes for which the selected performance parameters can be maintained almost independent of the temperature. This feature is desirable in applications requiring stability from the variations in the environmental conditions.**

## I. Introduction

In the THz frequency band (0.3–10 THz) the dynamic range of practical spectroscopy and imaging systems has to be improved in order to enable applications in fields like biomedical research, pharmaceutics, space or security industries [1]. In order to increase the dynamic range, one has either to raise the output power of the THz source or to enhance the sensitivity of detectors. With a view towards future low-cost practical applications, it is highly promising that emitters and detectors can be fabricated by reproducible, high-yield processes using the foundry-level complementary metal-oxide semiconductor (CMOS) technology [2].

A considerable improvement of the detectors' sensitivity can be achieved by cooling them. The prospects of CMOS devices operating at low temperatures have received considerable attention in the last decades [3]. Often, the device performance increases because the electron mobility rises considerably by cooling down a CMOS integrated circuit (a 5-7× better mobility was found in Ref. [4] upon cooling down to 4 K). Also the responsivity (i.e., the rectified voltage or current vs. power of the incident radiation) of TeraFETs improves upon cooling [5]. However, the enhanced mobility of the charge carriers is not the relevant aspect for the responsivity increase, as the TeraFET's performance does not directly depend on the carriers' mobility (it influences the performance indirectly via issues of impedance matching) [6]. It is rather the steepness of the rise of the carrier density with the gate voltage, which is the decisive factor here. As the steepness depends approximatively inversely on temperature [5], the device performance benefits from a lowering of the temperature.

Despite a higher cost and inconvenience of cooling, there are situations in the context of specific applications such as satellite-based earth exploration, for which CMOS devices designed to operate at cryogenic temperature promise to be beneficial.

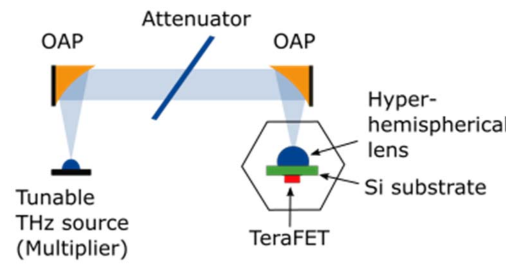


**Fig. 1.** Experimental setup for an optical and electrical characterization of liquid-nitrogen-cooled TeraFETs. OAP stands for off-axis paraboloidal mirror.

Here, we report on the performance of 90nm Si CMOS TeraFETs at moderate cryogenic temperatures (≥77 K).

## II. Detectors And Test Setup

The antenna-coupled THz detectors were implemented in 90-nm and 65-nm Si CMOS technology. The devices were designed in cooperation between Goethe University Frankfurt am Main and Vilnius University, and fabricated by TSMC (Taiwan). For the 90-nm device discussed here, the measured minimum optical NEP at room temperature is 44.5 pW/√Hz around 600 GHz, which is in good agreement with the previous characterization results, presented in [7].

The terahertz source system is tunable from 500 GHz to 750 GHz and is based on an all-electronic multiplier chain source, manufactured by Virginia Diodes Inc. The optical system (Fig. 1) consists of two off-axis paraboloidal mirrors with an effective focal length of 4 inch, used for collimation and focusing of the THz beam and a Si 8.9 dB attenuator. The THz radiation is coupled to the TeraFET from the bottom of the detector through a Si substrate and a hyper-hemispherical silicon lens. The cryostat is cooled down by liquid nitrogen. The TeraFET's rectified voltage was pre-amplified and measured with a dynamic signal analyzer Stanford Research SR785. For the determination of the responsivity and the NEP of the device, the power of the incoming radiation needs to be known [6-9]. It was measured with a calibrated Thomas Keating large-aperture detector capturing the total emitted THz power.

## III. Experimental Results

Fig. 2 presents the dependence of the static source-drain resistance $R_{DC}$ on the gate voltage $V_G$ at various temperatures in the range from 77 K (liquid-nitrogen temperature) to 297 K (room temperature). With decreasing temperature, the threshold voltage of the Si CMOS detector increases ($V_{th}$ lying in the range of 0.40-0.48 V), the resistance rises in the low-gate-voltage area (below the threshold voltage) and decreases above

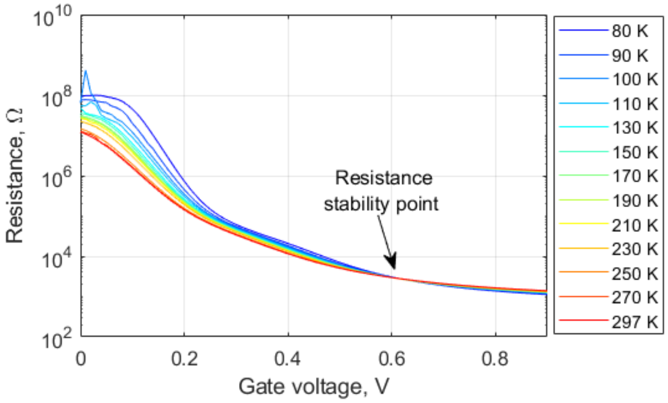


**Fig. 2.** Dependency of the total resistance $R_{DC}$ of Si TeraFET detector on the gate voltage for the temperature range 77-297 K.

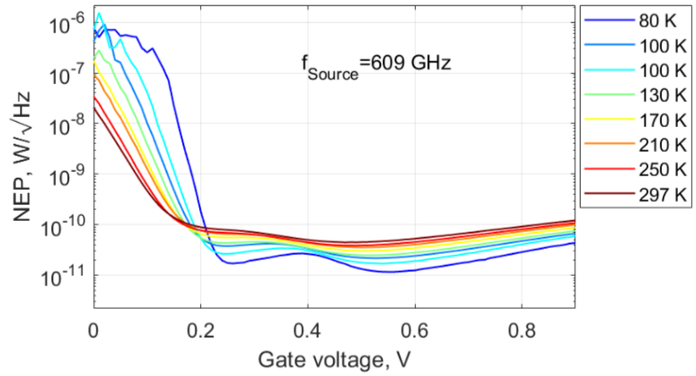


**Fig. 3.** Dependency of the optical NEP of a 90-nm detector on the gate voltage at different temperatures under continuous-wave irradiation at 609 GHz.

the threshold because of the increasing electron mobility. The extra resistance shoulder in the region of higher gate voltages (in the range 0.3-0.5 V) becomes more pronounced with decreasing temperature.

We performed parameter extraction by analyzing the source-drain resistance by a two-stage fit routine [10]. The following detector parameters were obtained by applying the fitting procedure for quasi-static I/V measurements: the threshold voltage $V_{th}$, the electron mobility and the total parasitic resistance $R_{ug}$. The parasitic resistance (which includes the contact resistances) decreases at lower temperature (from 400 Ω at 297 K to 300 Ω at 77 K). The extracted mobility increases from 160 $cm^2$/Vs at 297 K to 220 $cm^2$/Vs at 77 K. However, the 2DEG channel resistance dependency on temperature is non-trivial (see Fig. 2), because $R_{DC}$ is also depended on electron density, not only on electron mobility. The electron density lowers with decrease in temperature and detectors performance may be impaired despite the higher mobility values.

Fig. 3 presents the dependence of the NEP on the gate voltage in the investigated temperature range. With decreasing temperature, the NEP in the voltage range above 0.25 V decreases faster than the resistance, with its absolute minimum value slightly shifting to larger gate-bias voltages. Whereas different physical parameters which define responsivity and NEP depend on temperature in different manners, we find the minimum value of the NEP to scale linearly with temperature in the temperature range of the measurements. At 77 K and 609 GHz, the improvement amounts to a factor of 3.8, with a minimum optical NEP of 11.7 pW/√Hz.

It is important to note, that this device and other tested 90-nm and 65-nm CMOS TeraFETs not presented here possess gate bias regimes for which specific performance parameter (responsivity and resistance) can be maintained in a weak dependency on the temperature. For the responsivity (a data not shown) it corresponds to the gate voltage of about 0.38 V. For reference, the stability point of the channel resistance (Fig. 2) is in a completely different place – 0.615 V. Although the values of these parameters are not optimal at these voltage values, this feature may be useful and important for practical applications requiring stability from variations in the environmental conditions.

We remark in conclusion, that for TeraFET detectors whose responsivity is determined by distributed resistive mixing [11], the gate-voltage dependence of the responsivity, and with it that of the NEP, can be predicted qualitatively from the gate-voltage dependence of the channel resistance [12]. However, as the gate-voltage-dependent $R_{DC}$ curves displayed in Fig. 2 represents not only the resistance of the channel, but also include the contact and other parasitic resistances, it will be interesting in the future to investigate how the features of the $R_{DC}$ curves of Fig. 2 and especially their trends with temperature are reproduced in the measured NEP curves. These studies will also be instrumental to reveal the origin of the stability points addressed above.

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