Performance and performance variations of sub-1 THz detectors fabricated with 0.15 μm CMOS foundry process

S. Boppel, A. Lisauskas, V. Krozer and H.G. Roskos

Antenna-coupled field-effect transistors were integrated as multi-pixel (5 × 10) detector arrays for electromagnetic radiation between 550 and 600 GHz using commercial 0.15 μm CMOS process technology. Reported is a minimum optical noise-equivalent-power (NEP) of 43 pW/$\sqrt{\text{Hz}}$ and a maximum (capacitive-loading-limited) optical responsivity of 970 V/W (both values averaged). An electrical NEP of 9 pW/$\sqrt{\text{Hz}}$ is estimated. Inter-chip variations are analysed with a set of 15 samples showing a low standard deviation of less than 8% for both responsivity and NEP at the optimum operation point. Intra-chip variation is low for non-edge pixels. Both the very good NEP values and the low variations indicate that a cost-efficient CMOS process is well suitable for reliable fabrication of multi-pixel terahertz focal plane arrays.

Introduction: The development of a technology for the direct detection of terahertz (THz) radiation on the basis of field-effect transistors (FETs) operated above their transit-time limited cutoff frequency has progressed rapidly in recent years. Following the suggestion that plasma waves in the transistor's channel would lead to rectification of THz signals [1], the tentative experimental quantification of the responsivity and noise-equivalent-power (NEP) of this effect at 700 GHz in commercial silicon MOSFETs in 2006 [2] indicated the potential of the novel detector concept. The first application for imaging at 600 GHz with GaAs HEMTs [3] and the first development of CMOS focal-plane arrays (FPAs) with monolithically integrated antennas and amplifiers [4, 5] soon followed. The latter papers also pointed out that plasma-wave based rectification in the non-resonant limit, relevant for MOSFETs at room temperature, can be understood to be an extension of resistive mixing to the non-quasi-stationary case, as expressed now in the new terminology of distributed resistive self-mixing. The NEP determined for these antenna-coupled FPAs was found to be 300 pW/$\sqrt{\text{Hz}}$, limited by the integrated amplifiers. In order to determine the NEP and the responsivity of bare FETs, this Letter presents results of antenna-coupled detectors not containing integrated amplifiers. A 150 nm CMOS process technology instead of the 250 nm technology of [4, 5] was applied for improved performance. The intra- and inter-chip variations of the NEP and responsivity values were investigated.

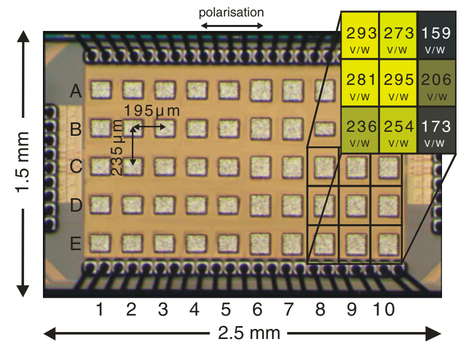

Fig. 1 *Micrograph of 5 × 10 CMOS detector array with microstrip patch antennas mostly resonant at 555 GHz (A8 at 610 GHz; A9 at 630 GHz)*

Intra-chip performance variations were studied at gate bias of 0.7 V (close to optimum NEP) and are visualised for bottom right corner by responsivity values averaged over four different samples. Responsivity values are reduced in row E, and strongly reduced at the vertical edge (column 10). The degraded performance likely to be related to ground-planes not extending far beyond antenna patches

Device fabrication: Detector chips as shown in Fig. 1 were fabricated with the LFoundry 150 nm CMOS process on a 1.5 × 2.5 mm^2 large silicon die. Every array comprises 5 × 10 pixels, each consisting of a microstrip patch antenna and a pair of NMOS FETs (320 nm gate width) arranged in differential configuration as in [4, 5]. Antenna and circuit parameters were varied in each array. All detectors except A6 to A10 were designed to operate at 590 GHz (A8 at 610 GHz; A9 at 630 GHz). However, the measured spectral responsivities show a general lowering of about 35 GHz from the design frequency (compare the inset of Fig. 2). The simulated (CST Microwave Studio) antenna impedance at resonance is about 300 Ω.

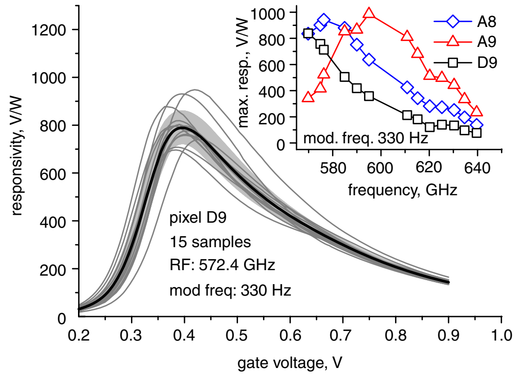

Fig. 2 *Inter-chip variation of responsivity of pixel D9 against gate voltage shown for 15 different samples (grey) and as their average curve (bold black) along with standard deviation (light grey)*

Inset: Spectral responsivity for three pixels (A8, A9, D9) with different design frequencies

FWHM detector bandwidth approximately 8%

Characterisation method: Samples were subjected to a focused beam of continuous-wave radiation delivered by a synthesiser-controlled millimetre-wave signal source. As this source only provides sufficient power in the range of 572.4 to 640 GHz, all samples had to be characterised at 572.4 GHz, slightly off resonance, except for pixels A8 and A9, whose resonances fall into this range. The beam power was determined with a calibrated large-area Thomas Keating power meter. The responsivity was determined by the self-referenced procedure described in [6], taking the detector pitch of 195 μm horizontally and 235 μm vertically as the effective detector area. With a modulation of the beam at 330 Hz for lock-in detection, capacitive loading effects were found to be significant at gate bias values around 0.39 V (maximal responsivity), but negligible above 0.5 V (and hence also at the minimal-NEP point at 0.7 V). NEP data were derived from the responsivity and thermal noise calculations based on DC-resistance measurements. Calculated thermal noise values were experimentally confirmed for a small set of samples by direct noise measurements in the voltage regime where loading effects can be neglected. To minimise spurious cavity effects, the standing-wave ratio (SWR) was reduced to less than 1.04.

Results: Using a set of 15 chips fabricated in the same process run, responsivity, NEP and their inter-chip variations were determined as a function of gate voltage for pixel D9 at 572.4 GHz, chosen because pixel D9 is surrounded by identical pixels. Fig. 2 shows the responsivity curves for all 15 samples (grey), as well as the average curve (bold black) and the standard deviation (light grey band). An average maximum responsivity (± standard deviation) of 801 (±72) V/W is achieved at a gate bias of 0.39 V. For a gate bias of 0.7 V, where the NEP is lowest, the average responsivity is 298 (±21) V/W, corresponding to 7%.

Fig. 3 shows the optical NEP of pixel D9 and its dependence on gate voltage for the same 15 samples as before (grey), as well as their mean curve (bold black) and standard deviation (light grey band). The NEP is found to be lowest at a gate bias slightly above the LFoundry specified threshold voltage of 0.7 V. The average minimum NEP is 51 (±4) pW/$\sqrt{\text{Hz}}$, corresponding to 8%, and a lowest (highest) minimum NEP of 42 (60) pW/$\sqrt{\text{Hz}}$, indicating acceptable inter-chip variations.

To analyse array uniformity, we measured the responsivity at 0.7 V (optimum bias with respect to NEP) for the 3 × 3 pixel matrix shown in Fig. 1 (bottom right corner). For each pixel, the responsivities of four different chips were averaged. Central detector pixels (C8, C9, D8, D9) show similar responsivities of 293, 273, 281, and 295 V/W, exhibiting a low variation with relative standard deviations of 4, 8, 6, and 7%. Pixels E8 and E9, which are very close to the bonding pads, show slightly reduced average responsivities of 236 and 254 V/W, and an increased relative standard deviation of 11 and 15%, respectively. Pixels C10, D10, and E10 at the vertical detector edge show notably reduced responsivities of 159, 206, and 172 V/W with relative standard deviations of 18, 9, and 20%. We attribute the reduction mainly to the

broken symmetry caused by the end of the ground-plane which modifies the antenna radiation pattern and gain.

Responsivity and NEP measurements were also carried out at resonance for pixel A8 at 576 GHz and A9 at 595 GHz on a set of six chips. They show approximately 15% better values than the off-resonance measurements reported above. Pixel A8 achieves an average maximum responsivity of 855 (±61) V/W and an average minimum NEP of 45 (±3) pW/$\sqrt{\text{Hz}}$. For pixel A9, an average maximum responsivity of 970 (±104) V/W and an average minimum NEP of 43 (±5) pW/$\sqrt{\text{Hz}}$ is obtained. The highest (lowest) maximum responsivity is 1090 (827) V/W and the lowest (highest) minimum NEP is 36 (50.5) pW/$\sqrt{\text{Hz}}$.

It is remarkable that the average minimum optical NEP values are lower than the minimum optical NEP of 50 pW/$\sqrt{\text{Hz}}$ recently reported for 650 GHz FET detectors fabricated with a significantly more costly 65 nm CMOS SOI process [7]. This can be attributed to the simulated low efficiency (12.5%) of the implemented folded-dipole antenna of [7] compared to the simulated 65 % efficiency of the microstrip patch antenna in this work.

Finally, we address the electrical performance of our detectors. Assuming an effective antenna area of the microstrip patches equal to their physical area (1.43×10^{-2} mm^2) and a simulated antenna efficiency of 65%, the electrical responsivity can be estimated from the measured optical responsivity of 340 V/W (see Fig. 3, inset) to be 1.7 kV/W, and the electrical NEP to be 9 pW/$\sqrt{\text{Hz}}$ (optical NEP: 43 pW/$\sqrt{\text{Hz}}$), both at 0.7 V gate bias and in resonance. These values are in good agreement with our simulations predicting 1.5 kV/W and 11 pW/$\sqrt{\text{Hz}}$, correspondingly.

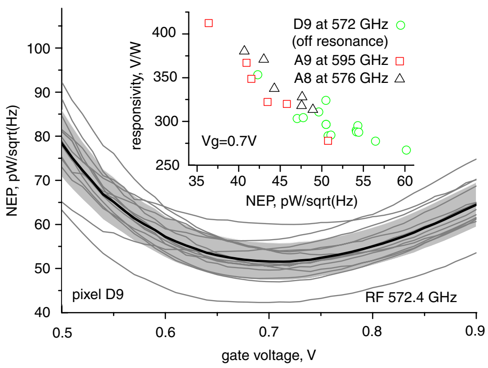

Fig. 3 *NEP values of pixel D9 against gate voltage shown for 15 different samples (grey), their average (bold black) and standard deviation (light grey)*

Average minimum optical NEP of 51 pW/$\sqrt{\text{Hz}}$ with standard deviation of 8% reported
Inset: Responsivity and NEP values for pixels A8, A9, D9 at 0.7 V gate bias
Data of pixels A8 and A9 taken at respective peaks of antenna responses (576 GHz, respectively 595 GHz), the data of D9 slightly off resonance

Conclusion: We report on THz detector arrays realised by microstrip-patch-antenna-coupled Si NMOS FETs for detection in the range of 550 to 600 GHz, fabricated in a 150 nm CMOS technology. Detector pixels exhibit a minimum average optical NEP of 43 pW/$\sqrt{\text{Hz}}$ and an average maximum optical responsivity of 970 V/W (without integrated amplifiers). We estimate the electrical NEP to be 9 pW/$\sqrt{\text{Hz}}$. Disregarding edge effects; the fabricated detector arrays show good uniformity of the responsivity and NEP values, which demonstrates the suitability for large-scale focal-plane arrays in this technology with high yield.

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One or more of the Figures in this Letter are available in colour online.

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