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THz detectors based on Si-CMOS technology field effect transistors – advantages, limitations and perspectives for THz imaging and spectroscopy

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ABSTRACT

Recent advances in THz detection with the use of CMOS technology have shown that this option has the potential to be a leading method of producing low-cost THz sensors with integrated readout systems. This review paper, based on authors' years of experience, presents strengths and weaknesses of this solution. The article gives examples of some hints, regarding radiation coupling and readout systems. It shows that silicon CMOS technology is well adapted to the production of inexpensive imaging systems for sub-THz frequencies. As an example paper presents the demonstrator of a multipixel Si-CMOS THz spectroscopic system allowing for chemical identification of lactose. The THz detectors embedded in this system were manufactured using the CMOS process.

1. Introduction

Field-effect transistors (FETs) exposed to THz radiation demonstrate a photovoltaic response. If the electromagnetic field energy is delivered to the given FET via an antenna (typically connected between the source and the gate terminals) or via bonding pads/wires, then a DC voltage is induced between the source and drain (usually unbiased) electrodes. In accordance with a commonly accepted theory, generation of the photoresponse is due to the transistor channel nonlinearity related to a simultaneous modulation of two parameters of electrons in the FET channel, namely their concentration and drift velocity. The photoresponse voltage is usually maximized if the channel is in a subthreshold regime. Detection of the THz radiation by FETs was predicted in 1996 in a work by Dyakonov and Shur [1]. Theory presented in that paper considered plasma excitations in the transistor channel and predicted propagation of plasma waves in the channel (plasmon resonances), as well as overdamped plasma oscillations (nonresonant modes) depending on the carrier mobility and excitation frequency.

Basically, in silicon technologies, the channel carrier mobility at room temperature is relatively low. Therefore, the plasma waves are usually overdamped and detectors are operating in a so called non-resonant mode. In this case plasma density is modulated by incoming THz radiation only in the vicinity of the source and the typical damping length is of the order of $l = 30\,\mathrm{nm}$ (frequency 300 GHz, mobility 300 $\mathrm{cm^2/Vs}$). For longer transistors 95% of the photovoltaic signal is generated at the distance $2l$ and remaining portion of the channel serves only as a resistive path providing DC output signal at the drain. In the case of nonresonant detection THz rectification may be also explained by extending classical resistive mixing theory to the so called distributed resistive mixing with its various amendments [2–5].

FET responsivity to THz radiation, discovered and extensively studied for 25 years, has made these devices useful for THz detection at room temperature. The early experiments have been focused on the use of THz for imaging and short-range communication. However, for the latter purpose Schottky diodes and HEMT transistors are predestined due to their higher operation speed. Imaging matrices based on detection on Schottky diodes integrated with the

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system of pixel amplifiers manufactured both in CMOS technology were reported in Ref. [6]6. Furthermore, after BiCMOS technology exploiting silicon–germanium (SiGe) heterojunction bipolar transistors (HBTs) [7] had been mastered, the devices and circuits produced in this process became competitive in both imaging and communication applications. The advanced systems for THz heterodyne detection developed with use of the BiCMOS process were recently reported in [8–10]. However, standard MOS transistors still remain a valuable option for imaging and spectroscopy, where the detector operation speed is not critical. This issue will be discussed in one of the following sections.

Complementary metal-oxide semiconductor (CMOS) technology has seen widespread use over the past dozen years for the fabrication of broadband terahertz detectors [11–15]. An example proving the broadband capabilities of direct detection using FET – CMOS detectors may be the solution implemented in the standard 150 nm CMOS technology [2]. For the realization of research projects based on the CMOS process there are several production tools such as MPW service (multi-project wafer – a service integrating a number of different circuit designs from various teams within one substrate and offering a certain amount of chips for a reasonable price). It should be pointed out that CMOS technology allows for easy integration of THz detectors with readout circuitry. A major disadvantage, however, is the large area required by the monolithically integrated antennas of each single detector. This area dominates and cannot be reduced because it is related to the THz radiation wavelength (sub-mm range). That makes R&D studies by means of the MPW services very expensive, especially if one considers detector focal plane arrays.

This work is an overview of the original developments of CMOS based THz detectors designed by the authors in the last decade. These developments were achieved using mainly a small Si foundry allowing for many degrees of freedom usually difficult to obtain in large IC CMOS facilities. In Section 2 we discuss the importance of detector substrates. Section 3 considers different sensing transistor layouts and describes some practical hints. Different antenna arrangements are briefly discussed in Section 4. This order is consistent with the order of the design cycle. Then, in Section 5, we summarize the work discussing different CMOS-THz detector applications, including imaging, and presenting original readout integrated circuits based on a multichannel chopper amplifier concept. Finally, in Section 6, an example of a specific spectroscopic application using resonant antennas for glucose detection is presented.

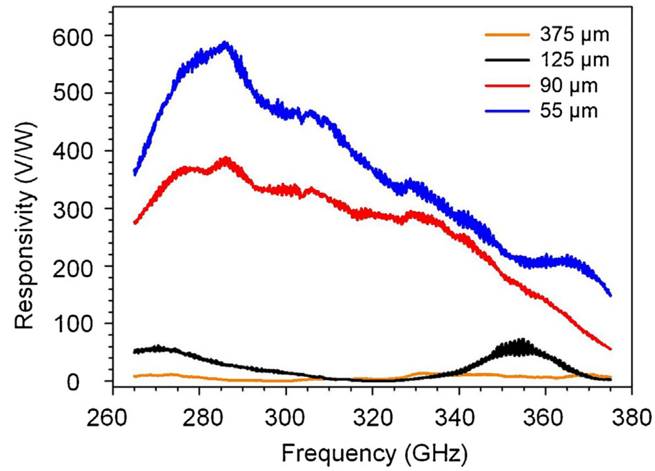

Fig. 1. Responsivity of the transistor integrated with a bow-tie antenna *vs.* thickness of the silicon substrate.

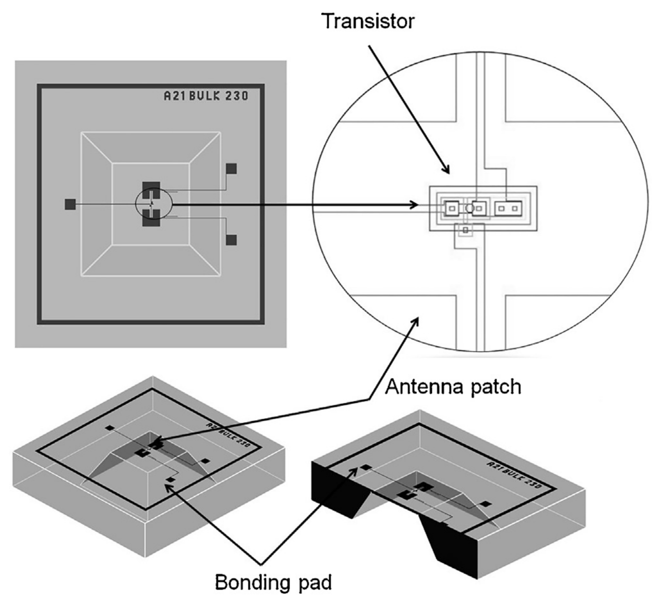

Fig. 2. Picture of an antenna integrated detector fabricated on a 40 μm membrane obtained by using an anisotropic chemical etching the substrate from the back using a mask of silicon nitride (ITE). The patch antenna equipped with sensing transistors is located on the membrane while the pads used for bonding are placed on a thick (non-etched) part of the die to allow trouble-free bonding.

2. Influence of the substrate

The proximity of the substrate with its high dielectric constant (and low resistivity used in most of MPW offers) is not conducive to the construction of efficient monolithically coupled antennas. This is because, without any special protections, most of incoming THz radiation will have tendency to penetrate to the substrate and propagates in it. This may lead to important losses of detector efficiency, as well as to detectors' cross-talk effects. To minimize the impact of the substrate one can use a metal layer (ground plane) that shields the antenna from the substrate. In such a solution, the antenna is produced at the highest level of metallization, and the ground plane is the lowest one. Typical (submicron) CMOS technology offers several metallization levels. This allows us to place the antenna at least a few micrometers above the substrate. An example of this solution can be found in Ref. [2]2 in which the connection of the antenna with transistor terminals is provided by vias. Such an elevated antenna may be capacitively coupled with the transistor as it was proposed for proprietary ITE technology in Ref. [16]16.

Another solution, used for non-shielded antennas, is thinning the detector substrate. Considerable thinning allows avoiding the propagation of electromagnetic waves in the form of so-called dielectric slab waveguide modes. Decrease in sensitivity of the detector mated with a bow-tie antenna, with respect to thickness of the substrate is shown in Fig. 1. Some studies on the thinning effect with suitable guidelines have been published recently [17]. Thinning of the detectors is not compatible with any standard processing. Thin structures, required to suppress substrate modes in sub-THz detectors based on FETs, may instead be obtained by grinding to the limit of several tens of microns. Obtaining thinner devices, suitable for higher frequencies, is possible in several non-standard technologies including the use of temporarily bonded carrier wafers. However, most of these techniques are very expensive. New features are offered by MEMS (Micro-Electro-Mechanical Systems) technology enabling the production of thin membranes (see Fig. 2).

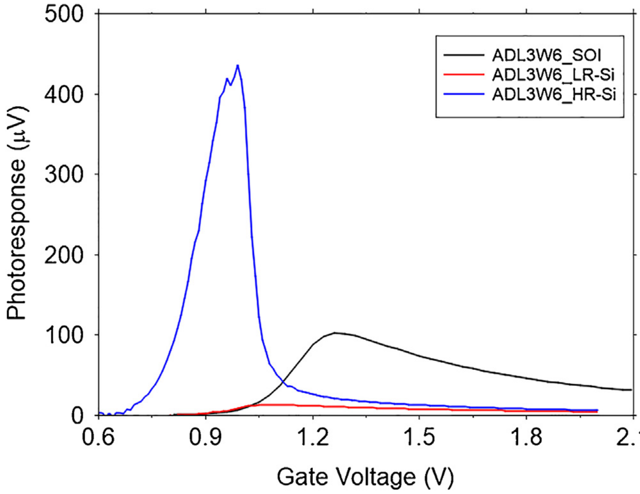

Fig. 3. Influence of the wafer type on responsivity of the detector integrated with a patch antenna for 340 GHz. The detectors were fabricated on the 40 µm thick silicon membranes etched within three types of substrates: LR bulk (red line), SOI with HR handle wafer (black), HR bulk (blue). In the last case, the particularly high detector response may be linked also to the higher transconductance of transistors manufactured on HR bulk substrates compared to the identical transistors in SOI technology (ITE).

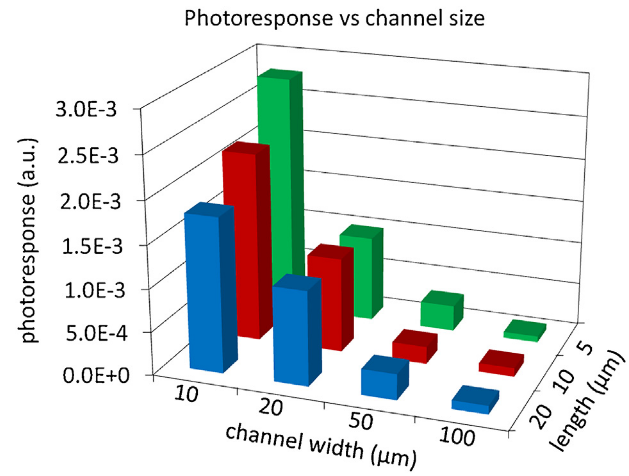

Fig. 4. Photoresponse of the detectors of different channel width for length 20, 10 and 5 µm (SOI-CMOS).

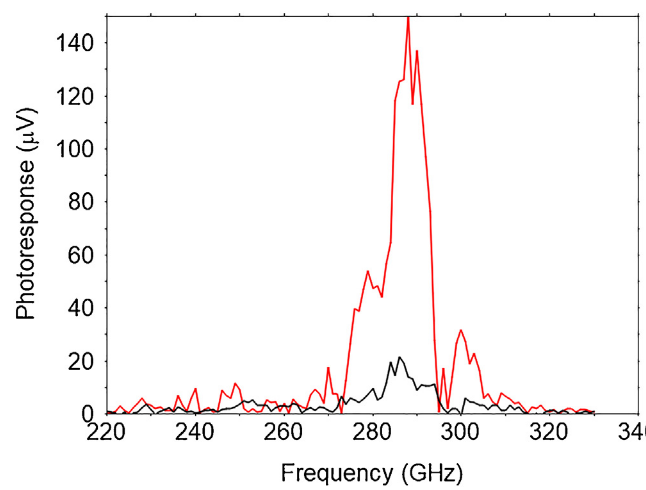

Fig. 5. Photoresponse of the detector *vs.* frequency fabricated using standard design rules (black curve) and with a violation of the rule (red curve) consisting in removing the channel stopper layer near the antenna.

The problem of THz energy loss in the form of the heat dissipated in the low-resistivity (LR) substrates may be solved by using SOI (silicon-on-insulator) wafers with high-resistivity (HR) silicon below the buried oxide or by using bulk HR silicon wafers (Fig. 3). These two options are typically not available with standard MPW services, but such a solution significantly improves the response of detectors. Moreover, they may be used to facilitate coupling of the incident radiation detector through the use of a HR silicon lens, and illumination of the detector from the backside.

3. Transistor layout – hints

Essentially, the layout of transistors has a significant impact on the value of parasitic elements affecting the efficiency of energy transfer from the antenna. A discussion on this subject in relation to CMOS technology can be found in Ref. 18, where the detailed analysis concerning parasitic elements has been carried out. We proved there that for standard operating conditions, no significant influence of the channel conductivity on the input impedance Z_{gs} can be observed. While the real part of this impedance is dominated by contact resistances and seems to be well matched with typical values available for simple antennas integrated within chips, the imaginary part is related mostly to the overlap capacitances between gate metallization and source. The measurements done on the relatively large transistors show that smaller transistors have always larger detectivity (see Fig. 4). The near hyperbolic dependence of responsivity on the width of the transistor indicates the dominant role of the source-gate capacitance shunting the incoming THz signal.

For this reason in the MPW services, which provides submicron devices, the smallest available transistors have usually the highest responsivity. There has been enormous progress recently in the design of detectors based on deep submicron CMOS technologies [2]. It appears that the detector gap between optoelectronic and microwave devices is beginning to close [19]. It should be pointed out, however, that specific design rules characteristic for chosen technology must be always observed. Sometimes one may negotiate a violation of a single design rule. In Fig. 5 a significant increase of the detector response due to the removal of a so-called channel stopper layer from the area beneath the integrated patch antenna is shown. Such a layer is of importance in the vicinity of transistor while its presence beneath the antenna lowers significantly the antenna efficiency. The example shown in Fig. 5 concerns the antenna design for 290 GHz (the case of single metallization) integrated with a 3/6 µm n-MOS transistor manufactured on the HR bulk substrate.

4. Integrated antenna choice

Designing an efficient antenna to be integrated within CMOS processing is not an easy task. Some restrictions have been already discussed in the paragraph concerning the dominant influence of substrate proximity. If one chooses the ground plane concept, to avoid penetration of the radiation into the substrate, the patch antenna is of primary choice. Some scientists have demonstrated the use of folded-dipole [20] or bow-tie [13] antennas. In any case, every design requires extensive numerical simulations, like those whose results are shown in the Fig. 6a, in order to assess the influence of antenna environment. Coupling impinging radiation through the HR substrate may offer the advantage of using a HR silicon lens to focus the THz radiation energy. For the higher frequencies, however, the antenna aperture drops down (see Fig. 6 showing simulated responsivity of patch antennas designed for

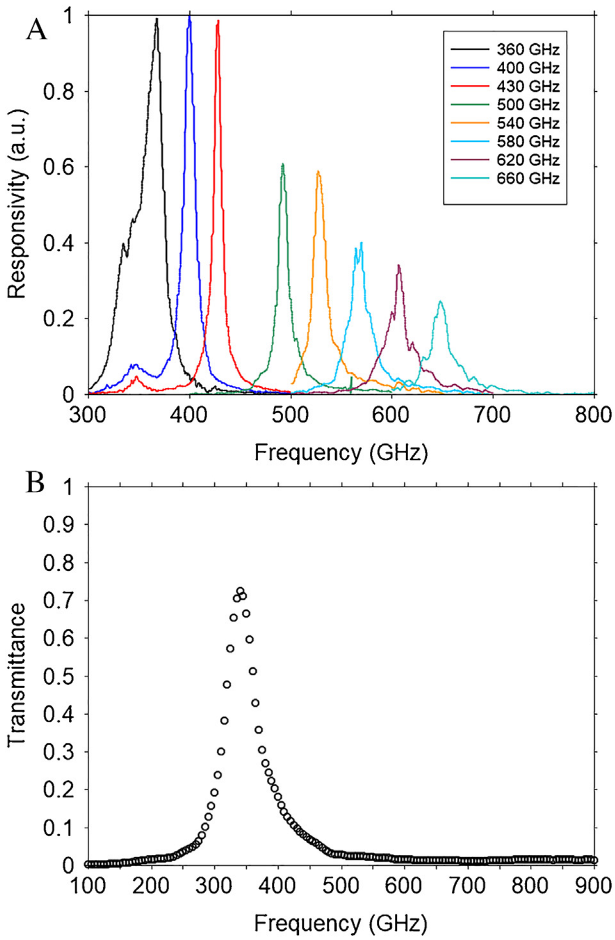

Fig. 6. Simulated responsivity of resonant patch antennas fabricated in bulk CMOS technology on a 20 μm silicon HR membrane (a). Fig. 6b shows an example of the mesh filter (crossed slits) transmittance measured with use of the time domain spectroscopy. Such a filter inserted within optical path reduces off-band response significantly.

spectrometry [21]), and antennas approach their RC limit [2] even if the detection mechanism still works.

There have been some efforts to minimize the RC constant of antenna systems. Significant achievements have been demonstrated using MEMS related technologies which are unfortunately not presently compatible with standard CMOS technologies, and include some off-line processing. It should be mentioned that large dimensions of antennas are not fully compatible with requirements of the submicron design rules, therefore, the metallization plane must be segmented in a specific way - not to violate the desired current distribution in the antenna. For broadband use, logarithmic antennas are widely used, especially if coupled with lenses [22]. Some work has been done concerning coupling with use of dual-grating-gate (DGG) high-electron-mobility transistors (HEMTs). In these detectors, the dual grating gate of a large area acts as an effective antenna and can operate in the THz range [23,24]. However, the use of the DGG concept for CMOS transistors has not been reported yet.

Essentially, the integrated antennas are used to increase detectors' sensitivity, or to provide a broadband coupling to the incident THz radiation. However, for spectroscopic applications one needs detectors with resonant response. This may be obtained by design of the resonant antennas. When their selectivity appears insufficient it may be enhanced by the use of suitable filters mounted in front of the detector. An example of frequency characteristics (TDS measurements [21]) of such a simple mesh filter (crossed slits cut in a thin metal foil) is shown in Fig. 6b. These filters may be used also to get rid of the detector response outside the antenna passband. The detector response outside the bandwidth of the antenna is usually significant, and may preclude its use for these applications.

5. Application related issues

THz imaging has experienced rapid development over the last decade, reaching a commercial status. Standard CMOS detectors seem to be optimal for THz imaging [25]. Commercially there are already available monochrome THz cameras, and recently a report on a multi-color imaging system has appeared [26]. A straightforward integration with the readout circuitry makes Si-FETs favorable for cameras operating in the real-time mode. They may be used in direct conversion or heterodyne modes and are very cheap in the mass production. To increase signal to noise ratio most of the imaging solutions typically require a THz source to be modulated and a lock-in technique to be used for the detection.

In the previous sections we have reported multidirectional experiments aimed at fabrication of efficient CMOS detectors of the THz radiation. In order to validate their applicability for imaging we used a measurement setup with a single detector to register radiation passed through an object. As an example may serve a n-type FET fabricated on the silicon substrate thinned to 125 μm and integrated with a bow-tie antenna. The device, assembled on a computer-controlled positioner, was working as a THz camera. This detector reached the record responsivity of 5 kV/W and the noise-equivalent power (NEP) below 10 pW/Hz$^{1/2}$ around 300 GHz [13]. The 292 GHz focused beam of 1 mm Full-Width at Half-Maximum (FWHM) was sourced by frequency multipliers. The lock-in system was used for the output signal measurements. Such a solution enabled obviously only slow measurements but was suitable to assess the advantages of several detectors. A THz image obtained with use of this simple imaging system is shown in Fig. 7. The figure shows an image of a piece of dry wood. The pixel resolution was of 300 μm × 300 μm. On the THz image, annual rings and xylem rays can be easily resolved. The dark areas of the annual rings represent latewood regions of low transmission. This is a good example that even single pixel systems may be used in several applications (in this case dendrology) not requiring high operation speed.

Besides the imaging experiments we have also performed specific studies aiming at the development of the complete readout system, targeted towards the processing of very small, DC voltage signals. Our main goal was to successfully replace the lock-in equipment with a dedicated integrated circuit (IC), which offers comparable parameters without the necessity of modulating the THz wave and using complex, expensive measurement equipment. The proposed solution is based on a chopper amplifier concept [27], enhanced for multichannel processing. A general operation principle of such a circuit consists of conversion of the input signals coming from the detector to a square wave, then of its selective amplification, finally followed by the AC signal conversion to a DC voltage. This idea provides the minimization of the influence of the input offset voltage and 1/f noise component (because only the AC component is amplified).

Our studies on readout circuit development resulted in the design of an integrated, multichannel circuit, dedicated to the 8-element pixel line (composed of FET-based THz detectors). In this chip, the overall signal path can be divided into two different parts: the individual channels for each particular detector and the common signal processing path. The first ones consist of input modulators and dedicated preamplifiers (based on G_m-C filters). The common part enables the second stage of the selective amplification (utilizing Multiple Feedback Topology), demodulation and output, low-pass filtration. Integrated circuit has been fabricated in

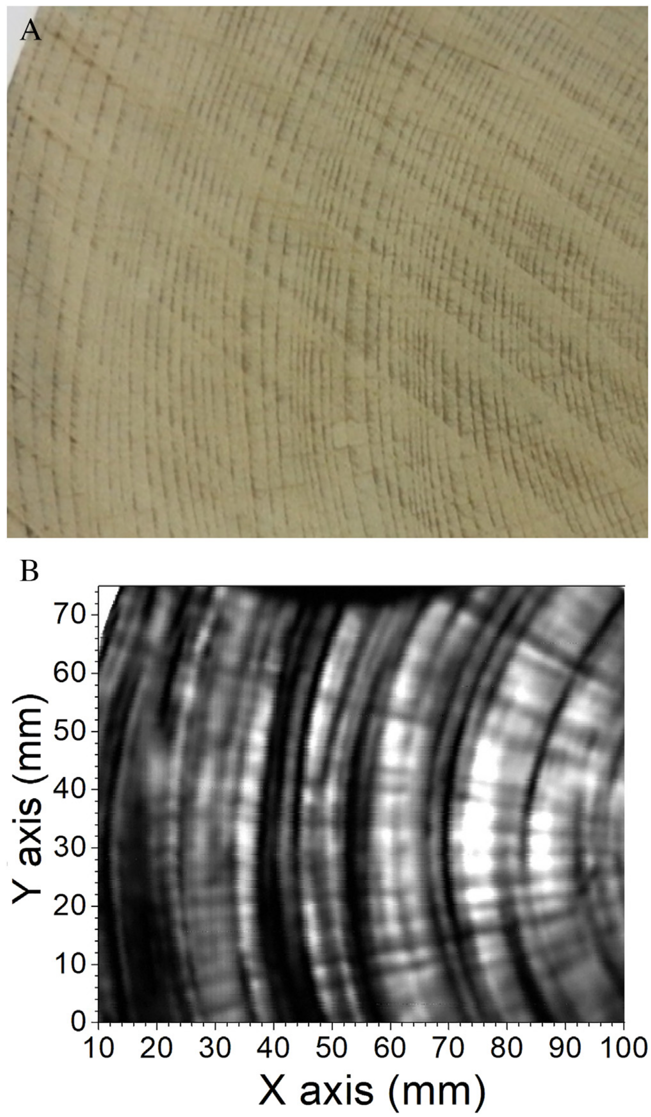

Fig. 7. Snapshot of a 1 cm thick wood slice and its THz image measured at 292 GHz (transmission mode) using a Si-CMOS THz detector.

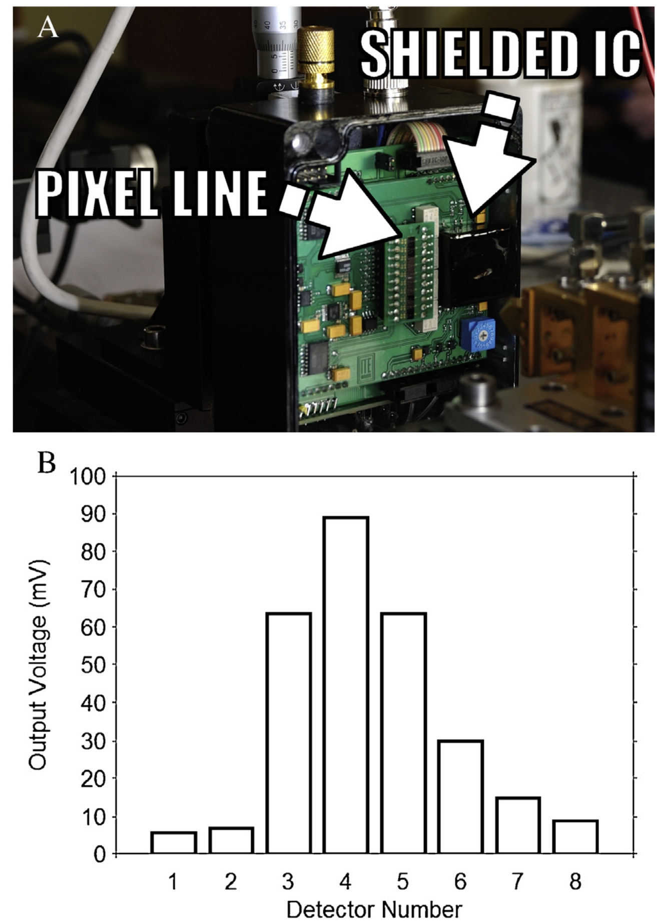

Fig. 8. THz measurements of the designed IC: (a) dedicated test set-up and (b) readout output voltages for 8-detector line, THz beam centered on the fourth pixel.

a standard, cost-effective AMS C35 silicon process (350 nm) with a total area of 10 mm^2 and 3.3 V power supply. Each channel of the designed chip ensures the input-referred noise density equal to 12 nVHz$^{-1/2}$ and provides the effective minimization of 1/f noise. The comprehensive description of the developed IC can be found in Ref. 28.

The proposed readout circuit has been verified in a real test-setup, containing dedicated measurement device (described in Ref. 29), 8-detector pixel line (fabricated in ITE proprietary silicon process) and Virginia Diodes, Inc. THz source (with frequency set to 340 GHz). Figure 8 presents a measurement device under test with some exemplary, experimental results. The presented bar chart shows the output signals from the subsequent detectors, denoted by the numbers under the trace. For each pixel, 2000 samples have been gathered - their median has been calculated and presented in the form of a single bar. The gain of the readout IC was set to 60 dB and we have obtained 58 dB signal-to-noise ratio (SNR) at the output of the system.

It should be mentioned that during the THz measurements described above neither beam modulation nor lock-in amplifier have been used. According to the assumptions, we have proven that the proposed readout circuit eliminates the necessity of modulating the THz wave and using complex and expensive measurement equipment. This feature may provide new possibilities in the field of FET detectors and readout electronics integration, resulting in the miniaturization of THz imaging and spectroscopy systems.

Several readouts, optimized for the characterization of the THz detectors, are based on the high-input impedance amplifiers. In such a configuration, a slight bias of the drain contact against the source may increase responsivity of the detector at the expense of an insignificant deterioration in the S/ N ratio [30]. In this setup, unlike the classic measurement of photovoltage (burdened with many problems due to the high resistance of the transistor channel in the subthreshold area), the measurement of the photocurrent may be preferred. In Fig. 9 some experiments with the current readout of the detection signal for the same sample as that shown in Fig. 1 are shown. A precision DC ammeter is used to this end, and the current signal is measured as the difference of the transfer characteristics with and without applied THz radiation. Figure 9a shows the current signal for three different substrate thicknesses, with the radiation frequency of around 290 GHz. The comparison with the voltage responsivity shown in Fig. 1 can be obtained by multiplying the current signal with the detector resistance at the corresponding bias point (Fig. 9b).

The availability of THz sources is a bottleneck for the development of many applications. For imaging they should be cheap, powerful, modulated (if a lock-in method is required), compact and easily integrated with suitable optics. The use of coherent sources has another serious disadvantage besides the cost in the form of the interferences coming from multiple reflections within the optical system between the source and the detector. We have tried several

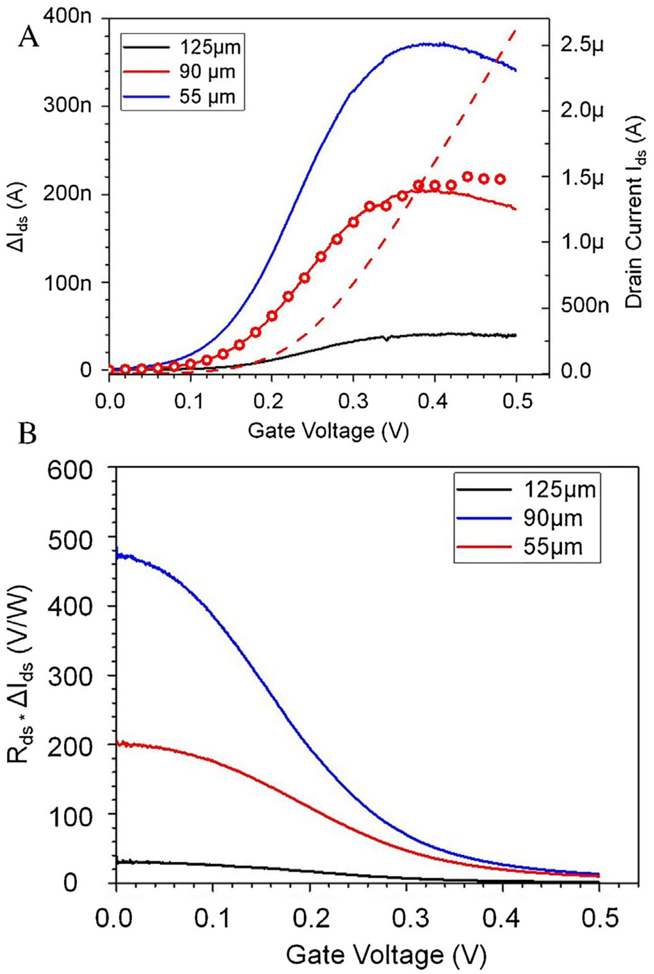

Fig. 9. (a) The current response ΔIds for three different substrate thicknesses (125 μm, 90 μm, and 55 μm, left scale) and radiation around 290 GHz. The static $I_{ds}(V_{gs})$ characteristic without radiation for the 90 μm thickness detector is shown in dashed red curve (right scale). Its first derivative δId/δVgs, divided by an arbitrary chosen constant (47 for 90 μm substrate) - shown in red open dots, almost exactly reproduces the shape of the photocurrent. (b) The value $R_{ds}\Delta I_{ds}(V_{gs})$ that can be compared with the experimental voltage responsivity attenuated by the loading effects at low gate voltage [17]. The photovoltage response on THz radiation follows the shape $\delta \ln(I_d)/\delta V_{gs}$, in the current-mode detection the response is proportional to $\delta I_d/\delta V_{gs}$.

options to reduce spurious interferences in experimental systems: tilted wave fronts, the application of absorbers around the optical path, different optical configurations, etc. We have found that the best solution is to modulate the source frequency. In Fig. 10 we show a photoresponse of the Si-MOSFET exposed to radiation emitted by a BWO (Backward Wave Oscillator). The frequency of radiation was tuned with a voltage applied to the cathode of the BWO. At the given voltage, the beam emitted by the BWO is quasi-monochromatic. The experimental system consisted of the FET positioned in front of the exit aperture of the BWO, at a distance of a few centimeters. A mechanical chopper was used to cut on/off the beam and no other optical elements were used. A power supply of the BWO allowed to modulate the BWO cathode voltage with a frequency of 2.5 kHz and an amplitude of up to 50 V which led to a decoherence of the beam. As one can observe in Fig. 10, the amplitude of interferences in the measured signal is substantial but can be essentially reduced when the modulation voltage is set on.

It should be pointed out that the recent capabilities brought by BiCMOS (Si-Ge) technology [31] can solve many problems providing THz sources suitable for on-chip spectroscopic systems and compact imagers.

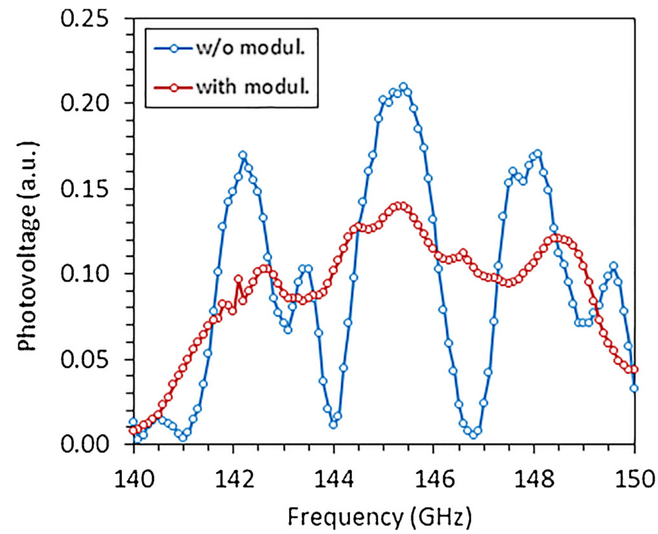

Fig. 10. A spectral response of a MOSFET without (blue line) and with (red line) source frequency modulation.

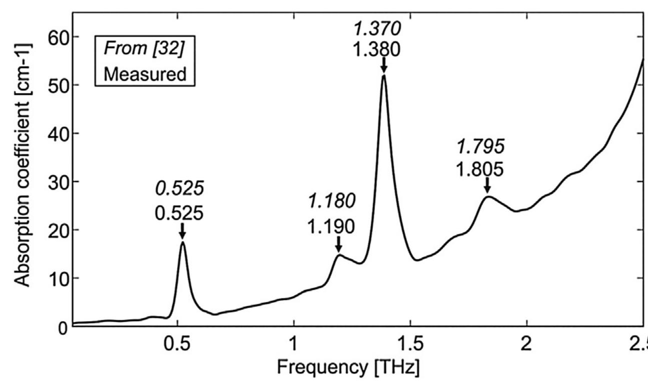

Fig. 11. Absorption coefficient of lactose measured by a TDS spectrometer – TeraView TPS spectra 3000. Peak frequencies agree with Ref. 32.

6. Spectrometry with CMOS detectors

As an example of the specific use of Si-CMOS detectors we present a system dedicated to lactose identification. Lactose is sugar that is found in milk. The ability of lactose detection could be important because of its intolerance by some people. Fortunately, the absorbance spectrum of the lactose shows a few sharp maxima in the THz region (Fig. 11).

Especially an absorption line centred at 525 GHz is promising because of the existence of relatively powerful multiplier based electronic sources in this range (in contrast to higher frequencies). Additionally, the responsivity of the detectors decreases for higher frequencies mainly due to decrease of the antenna aperture. The 8-pixel line of detectors equipped with patch antennas designed for several frequencies was fabricated. To recognize the shape of 525 GHz peak the following frequencies were chosen: 360 GHz, 400 GHz, 430 GHz, 500 GHz, 540 GHz, 580 GHz, 620 GHz, 660 GHz. The selection of the measurement frequencies was based on statistical analysis of the discriminative features taking into account the distorting effect of the atmosphere in the THz signatures propagation process. A signal identification procedure is described in the next paragraphs. The process of identification based on the comparison of the shape of a chosen peak instead of the positions of

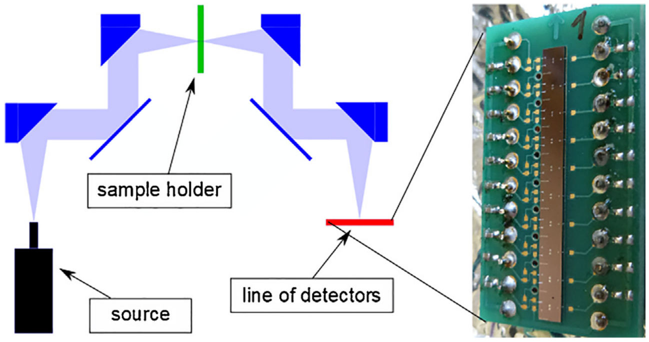

Fig. 12. A picture of the transmission spectroscopy setup based on the line of spectrally selective detectors placed in the chamber.

each peak proved to be effective. The system containing the VDI frequency multiplier as a source of radiation, the set of focusing mirrors, the sample holder, and the line of detectors was constructed (Fig. 12).

In the system dedicated to substance detection and identification, based on a narrowband source of radiation tuned in a wide range of frequencies, the atmosphere influence is essential. The water vapour present in the atmosphere attenuates and distorts the THz radiation on the way source/sample/detector. This situation determines the choice of the measurement frequencies. They should minimize the influence of the atmosphere and ensure characteristic spectral information which allows recognizing the sample. For the purpose of lactose detection, the first step was the collection of transmission spectra obtained with a TDS system in the range of 0.3–1.5 THz. To define the scale of changes in THz data caused by the atmosphere, the spectra were deformed by a convolution with collection of transmission spectra of the atmosphere for various humidity and different lengths of the radiation path generated using HITRAN [33] environment. The obtained set of results was analyzed statistically by a method based on a decision tree [34,35]. As a result a set of eight frequencies was obtained, for which the spectral features of the lactose do not change significantly under the influence of the atmosphere. The calculated set of frequencies was used to design and fabricate the line of narrowband detectors (Fig. 12) based on n-MOS transistors integrated with the patch antennas on a Si-membrane (like in the case shown in Fig. 2). In the constructed setup, containing the THz source and the line of detectors, the spectral measurements of the same substance that was tested in the TDS system were performed. The gathered results were the basis to extract the "pattern" of lactose and a decision model. It was achieved by the combined method of a principal component analysis (PCA) [35,36] and quadratic discriminant analysis (QDA) [35,37]. The PCA was used to decrease the dimension of analyzed data and the QDA to indicate the areas separating a membership to a given class of substances (in our case lactose). The developed decision model compares the input data (8-dimension data from the line of detectors) from the investigated sample with a pattern of lactose. The identification module in the prepared measurement setup was verified by testing with a set of samples. We compared: lactose, sucrose, glucose, polyethylene, RDX, PABA, PETN, tartaric acid, and uric acid. Lactose was identified with the accuracy of 98%. As it was pointed out, the process of identification is entirely different from those well-known from spectrometry since the procedure compares not the continuous spectra but values of the signal in eight discrete points with the data stored in a database. It greatly simplifies such a system and makes the identification independent from the influence of water vapour or other substances, which may absorb the radiation accidentally.

The system was equipped with a user friendly interface working on PC shown in Fig. 13. It helps to make decision if a given sample is similar or different from the pattern. According to our discernment, this is the first case of using CMOS detectors integrated with resonant antennas to identify the chemical composition of a sample.

7. Conclusions

The use of the standard CMOS technology for the fabrication of the terahertz detectors is a productive and cost-effective solution in particular in relation to sensors and small imaging systems working in the sub-THz region. However, a lot of space is occupied by the antenna, which makes a large matrix system relatively expensive. A serious problem is the reduction of the antenna efficiency caused by substrate losses. For the systems based on a single detector,

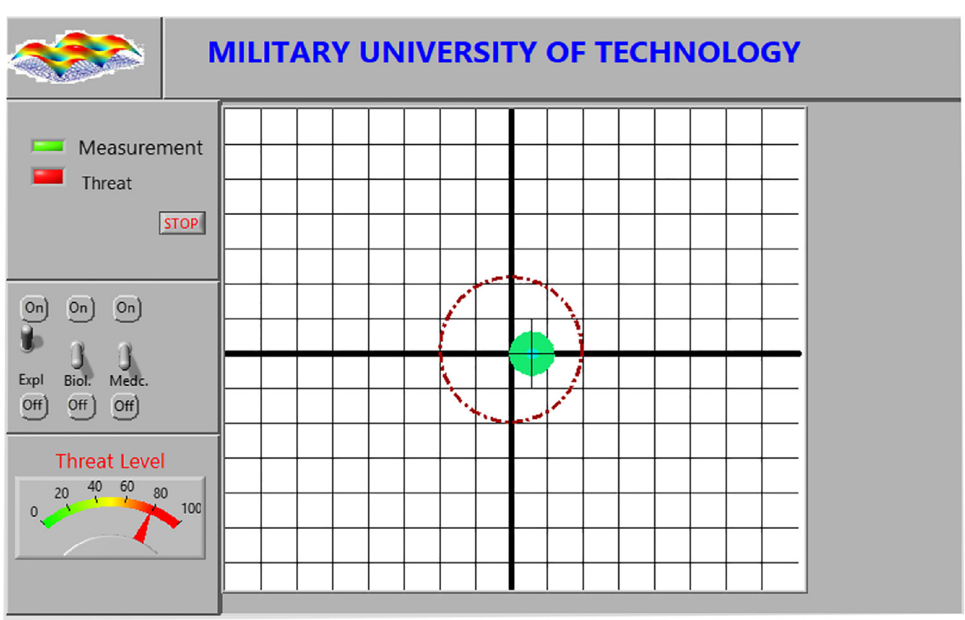

Fig. 13. A picture of GUI prepared for the identification system. Prepared algorithm shows the green point in a different distance from the center of decision area. If this point is placed inside the red circle, it means that measured substance agrees with the pattern.

good results are achieved by the use of high-resistivity substrate and backside illumination through the integrated silicon lenses. In any other solution, the substrate should be as thin as possible or the antenna shielded from the substrate. Dedicated readouts can be easily integrated into any CMOS technology including the digital interfaces required for broadband telecom applications. Photocurrent measurements using transconductance amplifiers or applications using chopper amplifiers for photovoltage measurements can bring significant benefits, especially on the imaging systems using unmodulated THz sources. Applications requiring selectivity should employ an antenna that is placed either as far away as possible from the lossy technological layers or shielded. They may also use the appropriate filters based on metamaterials to increase selectivity and to attenuate the out of band signals. Finally, the demonstrator of a simple spectrometer for lactose identification, working within sub-THz band and based on CMOS transistors was presented.

Authors contribution

Jacek Marczewski – conceptualization, paper writing, co-ordination.
Dominique Coquillat – measurements (THz).
Wojciech Knap – consultant, paper drafting.
Cezary Kolacinski – ASIC read-out - concept and design.
Pawel Kopyt – antenna simulations.
Krzysztof Kucharski – CMOS technology designer.
Jerzy Lusakowski – experiments (physics).
Dariusz Obrebski – detector layouts designer, read-out interface designer.
Daniel Tomaszewski – I–V measurements of devices, modeling and characterization.
Dmitriy Yavorskiy – measurements (THz).
Przemyslaw Zagrajek – measurements (THz).
Radoslaw Ryniec – data processing concept for spectroscopy, GUI designer.
Norbert Palka –Time Domain Spectroscopy measurements.

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References

[1] M.I. Dyakonov, M.S. Shur, Plasma wave electronics: novel terahertz devices using two dimensional electron fluid, IEEE Trans. Electron. Dev. 43 (10) (1996) 1640–1645.
[2] S. Boppel, A. Lisauskas, M. Mundt, D. Seliuta, L. Minkevicius, I. Kasalynas, G. Valusis, M. Mittendorff, S. Winnerl, V. Krozer, H.G. Roskos, CMOS integrated antenna-coupled field-effect transistors for the detection of radiation from 0.2 to 4.3 THz, IEEE Trans. Microw. Theory 60 (12) (2012) 3834–3842.
[3] A. Lisauskas, U. Pfeiffer, E.O. Ojefors, P.H. Bolivar, D. Glaab, H.G. Roskos, Rational design of high-responsivity detectors of terahertz radiation based on distributed self-mixing in silicon field-effect transistors, J. Appl. Phys. 105 (11) (2009) 114511.
[4] I. Khmyrova, Yu. Seijyou, Analysis of plasma oscillations in high electron mobility transistor like structures: distributed circuit approach, Appl. Phys. Lett. 91 (2007) 143515.
[5] S. Preu, S. Kim, R. Verma, P.G. Burke, M.S. Sherwin, A.C. Gossard, An improved model for non-resonant terahertz detection in field-effect transistors, J. Appl. Phys. 111 (2012) 024502.
[6] H. Ruonan, Z. Yaming, K. Youngwan, K. Dae Yeon, S. Hisashi, A. Ehsan, K.O. Kenneth, Active terahertz imaging using Schottky diodes in CMOS: array and 860-GHz Pixel, IEEE J. Solid-State Circuits 48 (10) (2013) 2296.
[7] M. Schroeter, T. Rosenbaum, P. Chevalier, B. Heinemann, S.P. Voinigescu, E. Preisler, J. Boeck, A. Mukherjee, SiGe HBT technology: future trends and TCAD-based roadmap, Proc. IEEE 105 (6) (2017) 1068–1086, http://dx.doi.org/10.1109/JPROC.2015.2500024.
[8] K. Statnikov, J. Grzyb, B. Heinemann, U.R. Pfeiffer, 160-GHz to 1-THz multi-color active imaging with a lens-coupled SiGe HBT chip-set, IEEE Trans. Microw. Theory 63 (2) (2015) 520–532.
[9] J. Grzyb, U. Pfeiffer, THz direct detector and heterodyne receiver arrays in silicon nanoscale technologies, J. Infrared Millim. Terahertz Waves 36 (10) (2015) 998–1032.
[10] R. Lachner, Towards 0.7 terahertz silicon germanium heterojunction bipolar technology - the DOTSEVEN project, ECS Trans. 64 (6) (2014) 21–37.
[11] U. Pfeiffer, E. Ojefors, A600-GHz CMOS focal-plane array for terahertz imaging applications, 34th European Solid-State Circuits Conference (ESSCIRC) (2008), http://dx.doi.org/10.1109/ESSCIRC.2008.4681804, 110.
[12] F. Schuster, H. Videlier, A. Dupret, D. Coquillat, M. Sakowicz, J. Rostaing, M. Tchagaspanian, B. Giffard, W. Knap, A broadband THz imager in a low-cost CMOS technology, IEEE International Solid State Circuits Conference Digest of Technical Papers (ISSCC) (2011), http://dx.doi.org/10.1109/ISSCC.2011.5746211, 42.
[13] F. Schuster, D. Coquillat, H. Videlier, M. Sakowicz, F. Teppe, L. Dussopt, B. Giffard, T. Skotnicki, W. Knap, Broadband terahertz imaging with highly sensitive silicon CMOS detectors, Opt. Express 19 (8) (2011) 7827.
[14] R. Al Hadi, H. Sherry, J. Grzyb, Y. Zhao, W. Foerster, H.M. Keller, A. Cathelin, A. Kaiser, U.R. Pfeiffer, A 1 k-pixel video camera for 0.7–1.1 terahertz imaging applications in 65-nm CMOS, IEEE J. Solid-State Circuit 47 (2012) 2999–3012.
[15] A. Lisauskas, S. Boppel, M. Saphar, V. Krozer, L. Minkevicˇius, R. Venckevicius, D. Seliuta, I. Kasalynas, V. Tamosiuunas, G. Valusis, H.G. Roskos, Detectors for terahertz multi-pixel coherent imaging and demonstration of real-time imaging with a 12x12-pixel CMOS array, Proceedings of the SPIE, 8496 Terahertz Emitters, Receivers, and Applications III (2012), http://dx.doi.org/10.1117/12.930086, p. 84960J.
[16] P. Kopyt, J. Marczewski, K. Kucharski, J. Lusakowski, W. Gwarek, Planar antennas for THz radiation detector based on a MOSFET, Houston (US), 2–7 October, 36th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz) (2011), http://dx.doi.org/10.1109/IRMMW-THz.2011.6105129.
[17] D. Coquillat, J. Marczewski, P. Kopyt, N. Dyakonova, B. Giffard, W. Knap, Improvement of terahertz field effect transistor detectors by substrate thinning and radiation losses reduction, Opt. Express 24 (1) (2016) 272–281.
[18] P. Kopyt, B. Salski, J. Marczewski, P. Zagrajek, J. Łusakowski, Parasitic effects affecting responsivity of sub-THz radiation detector built of a MOSFET, J. Infrared Millim. Terahertz Waves 36 (11) (2015) 1059–1075.
[19] S. Boppel, A. Lisauskas, M. Bauer, M. Mundt, R. Venckevicius, L. Minkevicius, D. Seliuta, I. Kasalynas, B. Khamaisi, E. Socher, G. Valusis, V. Krozer, H.G. Roskos, Optimized tera-FET detector performance based on an analytical device model verified up to 9 THz, Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), 38th International Conference on (2013), http://dx.doi.org/10.1109/IRMMW-THz.2013.6665574.
[20] U.R. Pfeiffer, E. Ojefors, A. Lisauskas, H.G. Roskos, Opportunities for silicon ant mmWave and Terahertz frequencies, Bipolar/BiCMOS Circuits and Technology Meeting, 2008. BCTM 2008. IEEE (2008) 149–156, http://dx.doi.org/10.1109/BIPOL.2008.4662734.
[21] P. Kopyt, B. Salski, P. Zagrajek, D. Obrebski, J. Marczewski, Modeling of silicon-based substrates of patch antennas operating in the sub-THz range, IEEE Trans. Terahertz Sci. Technol. 7 (4) (2017) 424–432.
[22] A.D. Semenov, H. Richter, H.-W. Hubers, G. Burghardt, A. Smirnov, K.S. Il'in, M. Siegel, J.P. Karamarkovic, Terahertz performance of integrated lens antennas with a hot-electron bolometer, IEEE Trans. Microw. Theory 55 (2) (2007) 239–247.
[23] T. Watanabe, S. Boubanga-Tombet, Y. Tanimoto, D. Fateev, V. Popov, D. Coquillat, W. Knap, Y. Meziani, Y. Wang, H. Minamide, H. Ito, T. Otsuji, InP- and GaAs-based plasmonic high-electron-mobility transistors for room-temperature ultrahigh-sensitive terahertz sensing and imaging, IEEE Sens. J. 13 (1) (2013) 89–99.
[24] D. Coquillat, P. Zagrajek, N. Dyakonova, K. Chrzanowski, J. Marczewski, Y. Kurita, A. Satou, K. Kobayashi, S. Boubanga Tombet, V.V. Popov, T. Suemitsu, T. Otsuji, W. Knap, Detection of terahertz and mid-infrared radiations by InP-based asymmetric dual-grating-gate HEMTs, Tucson (US), 15–19 September, 39th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz) (2014), http://dx.doi.org/10.1109/IRMMW-THz.2014.6956522.
[25] U.R. Pfeiffer, E. Ojefors, A. Lisauskas, D. Glaab, H.G. Roskos, A CMOS focal-plane array for terahertz imaging, Radio Frequency Integrated Circuits Symposium, RFIC 2009. IEEE (2009) 433–436, http://dx.doi.org/10.1109/ICIMW.2008.4665429.
[26] M. Bauer, R. Vencievicius, I. Kasalynas, S. Bopel, M. Mundt, L. Mikevicius, A. Lisauskas, G. Valusis, V. Krozer, H.G. Roskos, Antenna-coupled field effect transistors for multi-spectral imaging up to 4.25 THz, Opt. Express 22 (16) (2014) 19235–19241.
[27] C.C. Enz, G.C. Temes, Circuit techniques for reducing the effects of op-amp imperfections: autozeroing, correlated double sampling, and chopper stabilization, Proc. IEEE 84 (11) (1996) 1584, http://dx.doi.org/10.1109/5.542410.
[28] C. Kolacinski, D. Obrebski, P. Zagrajek, Integrated, multichannel readout circuit based on chopper amplifier concept for fet-based THz detectors, Circ. Syst. Signal Process. 37 (3) (2018) 984–1006.

[29] D. Obrebski, C. Kolacinski, M. Zbiec, P. Zagrajek, The multi-channel small signal readout system for THz spectroscopy and imaging applications, 2016 IFIP/IEEE International Conference on Very Large Scale Integration (VLSI-SoC) (2016) 1–6, http://dx.doi.org/10.1109/VLSI-SoC.2016.7753562.
[30] A. Lisauskas, S. Boppel, J. Matukas, V. Palenskis, L. Minkevičius, G. Valušis, P. Haring-Bolívar, Hartmut G. Roskos, Terahertz responsivity and low-frequency noise in biased silicon field-effect transistors, Appl. Phys. Lett. 102 (2013) 153505.
[31] U.R. Pfeiffer, Y. Zhao, J. Grzyb, R. Al Hadi, N. Sarmah, W. Förster, H. Rücker, B. Heinemann, A 0.53 THz reconfigurable source module with up to 1 mW radiated power for diffuse illumination in terahertz imaging applications, IEEE J. Solid-State Circuits 49 (12) (2014) 2938–2950.
[32] M. Schirmer, M. Fujio, M. Minami, J. Miura, T. Araki, T. Yasui, Biomedical applications of a real-time terahertz color scanner, Biomed. Opt. Express 1 (2) (2010) 354–366.
[33] www.hitran.org.
[34] L. Breiman, Random forest, Mach. Learn. 45 (5) (2001) 5–32.
[35] R.O. Duda, P.E. Hart, D.G. Stork, Pattern Classification, A Wiley-Interscience Publication, 2001.
[36] F.R.S. Karl Pearson, LIII. On lines and planes of closest fit to systems of points in space, Lond. Edinburgh Dublin Philos. Mag. J. Sci. 2 (11) (2010) 559–572, http://dx.doi.org/10.1080/14786440109462720.
[37] T.M. Cover, Geometrical and statistical properties of systems of linear inequalities with applications in pattern recognition, IEEE Trans. Electron. 14 (3) (1965) 326–334.