Proceedings of the 47th International School and Conference on the Physics of Semiconductors “Jaszowiec 2018”

Application of High-Resistivity Silicon Substrate for Fabrication of MOSFET-Based THz Radiation Detectors

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It is well known that integration of THz detectors with silicon lenses (made of high-resistive Si) brings several advantages including a significant increase of the detector responsivity due to the increased aperture of the detector. THz detectors manufactured in CMOS technology are based usually on a n-type sensing transistor monolithically integrated with an antenna fabricated in the same process sequence. Integration of such a detector with Si lens is not an easy task. The simplest way is to introduce the THz radiation through the silicon lens glued to the substrate, which then has to be made (if possible) of high-resistive silicon to avoid energy losses. Following results of several experiments described in this paper our CMOS process sequence has been modified both with respect to the substrate change and then maximizing of the antenna efficiency by removal of heavily doped areas of the channel stopper in its vicinity

DOI: 10.12693/APhysPolA.134.966

PACS/topics: 85.30.Tv, 85.60.Gz, 42.79.Pw

1. Introduction

NMOS transistors have been used as THz detectors for many years [1, 2]. The detection mechanism is demonstrated by a generation of a DC drain–source voltage in the irradiated MOSFET with the open drain terminal. The effect was theoretically predicted by Dyakonov and Shur [3] and this phenomenon led to several applications in imaging and, more recently, in telecommunication areas [4, 5]. It is a common practice to use CMOS technology to enable the integration of detectors with antennas and readout systems. An important challenge in such detectors is maximization of electromagnetic (EM) wave energy deposition in the transistors. Two solutions seem to be favorable. One consists in fabrication of an antenna separated from the lossy silicon substrate by a metal screen. According to the second one, requiring a high resistivity (HR) Si substrate, the bottom of the structure is exposed to THz radiation and the energy is deposited through the entire volume, preferably across the highly resistive silicon lens attached to the underside. The latter method minimizes the energy dissipation, increases the aperture of the detector, and reduces interferences. In this paper we are dealing with a technology to be compatible with HR substrates (including HR-Si lenses) to minimize losses in the vicinity of mating integrated antenna.

2. Experiment

In this experiment several detector types were manufactured on silicon membranes formed in four-inch HR silicon wafers. The membranes were used to minimize EM energy losses in the Si substrate acting like a dielectric waveguide [6]. All the detectors were equipped with two phased patch antennas connected with the source and drain terminals, design of which is shown in Fig. 1. The antennas in different detectors were designed for different frequencies. The metallization underneath the membrane was the ground plane of the antenna. Therefore, the HR silicon was acting as a relatively lossless insulator used for antenna construction. Next, following the analysis of the extensive photoresponse measurements (see the next sections), we developed the manufacturing process leading to the highest detectivity. Using the optimized approach we fabricated the detector integrated with a Si-HR lens and with a wide-band log-periodic antenna receiving the THz radiation through the entire substrate.

3. Device manufacturing

The core technology was based on the process presented in [7]. The detectors fabricated on the HR Si bulk wafers appeared to be more sensitive than their counterparts on silicon on insulator (SOI) substrates with HR Si under buried oxide (handle wafer) — Fig. 2. Therefore, all further experiments were done with HR bulk silicon substrates having the resistivity of 10 kΩ cm.

The detectors were fabricated using the technology consisting of three process groups: micromachining operations (to form the membranes), modification of the near-surface area (doping and annealing) necessary for manufacturing of transistors on HR Si, and several elements of standard CMOS process sequence.

The 40 μm thick membranes were formed at the beginning of processing by means of anisotropic chemical KOH etching of the substrate backside. The modification of

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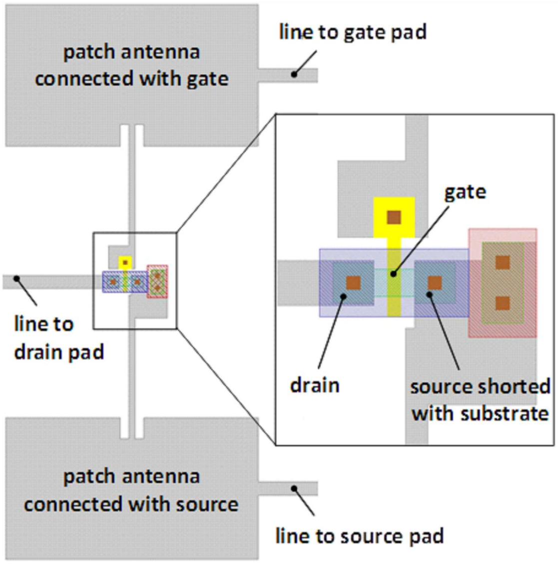

Fig. 1. A layout of the MOSFET (channel width $W = 6$ μm, length $L = 3$ μm) with patch antennas designed for radiation frequency 340 GHz, and connected with source and gate.

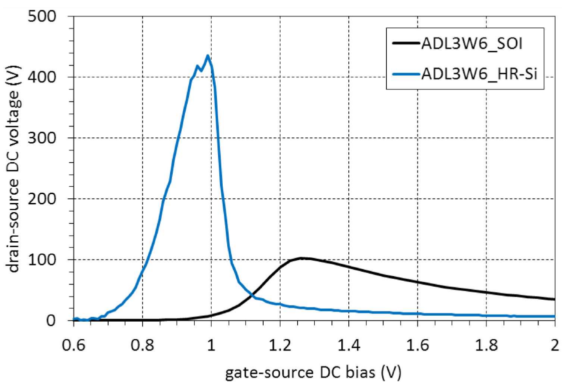

Fig. 2. Photoresponse of the n-FET (width $W = 6$ μm, and length $L = 3$ μm) coupled with a patch antenna for 340 GHz.

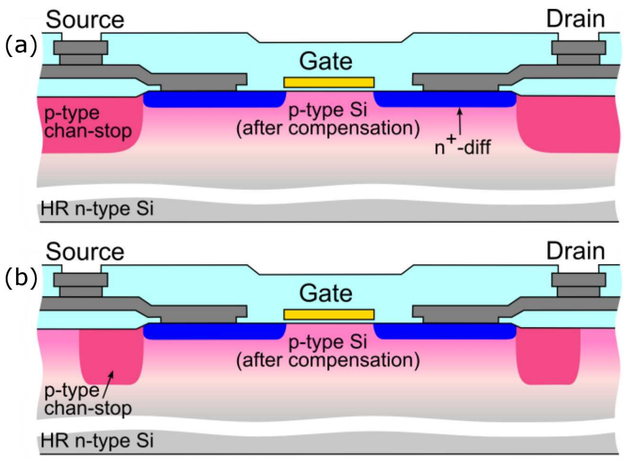

Fig. 3. Two versions of nMOSFETs with (a) standard channel stopper layer outside the transistor active areas, (b) modified channel stopper layer formed locally.

the near-surface area was an important part of processing aiming at obtaining requested profile of the doping density allowing for fabrication of the transistors. That was achieved by ion implantation and suitable thermal treatments. These non-standard steps were completed by some CMOS processes necessary to fabricate the transistors (in our case with poly-Si self-aligned gate and Al metallization).

During the measurements of the photoresponse, we came to the conclusion that the antenna efficiency was decreased by a so-called channel stopper (CS), i.e. a thin, relatively strongly doped silicon area formed in the standard CMOS technology to prevent from parasitic current paths among the transistors. This feature of the CSs has made them non-depleted. Following the standard design rules, the CS regions in the THz detectors were placed also directly under the antennas. Therefore, this has led to enhanced EM energy losses in the detectors. Therefore, in the next step, the layout of CS areas in the vicinity of the antennas was modified, keeping CS only near the transistors (where it was necessary — see Fig. 3).

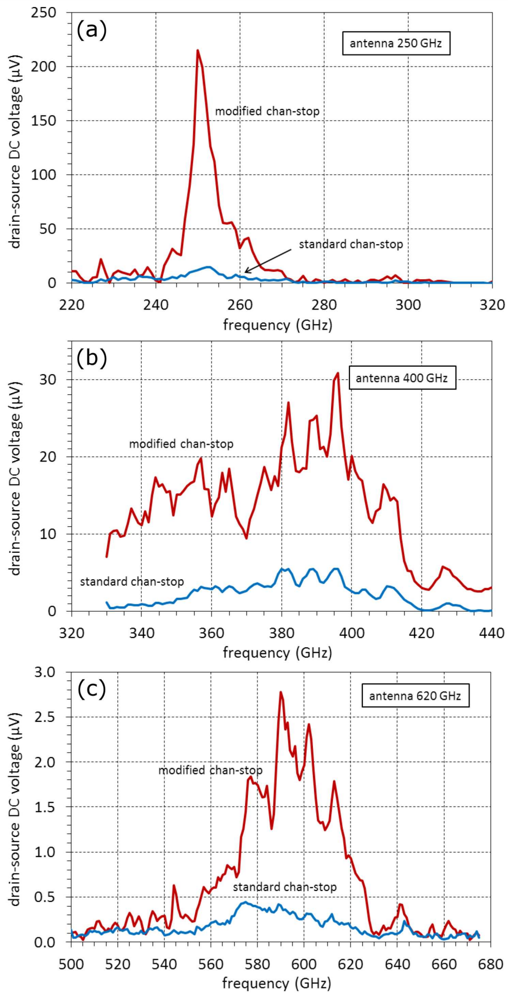

Fig. 4. The impact of channel stopper modification on the frequency characteristics of detectors designed for (a) 250, (b) 400, and (c) 620 GHz, respectively.

4. Measurements and discussion

A measurement setup included frequency multipliers from Virginia Diodes, Inc. as a source of the THz radiation in the range from 220 GHz to 650 GHz. A low output signal was measured with a lock-in system (Stanford Research Systems SR830) based on modulation at 187 Hz, and connected with a low-noise amplifier (SR550). Neither lenses nor mirrors were used to avoid the interferences, caused by possible multiple reflections. In Fig. 4 we show the photoresponse of detectors designed for different frequencies prior and after CS modification.

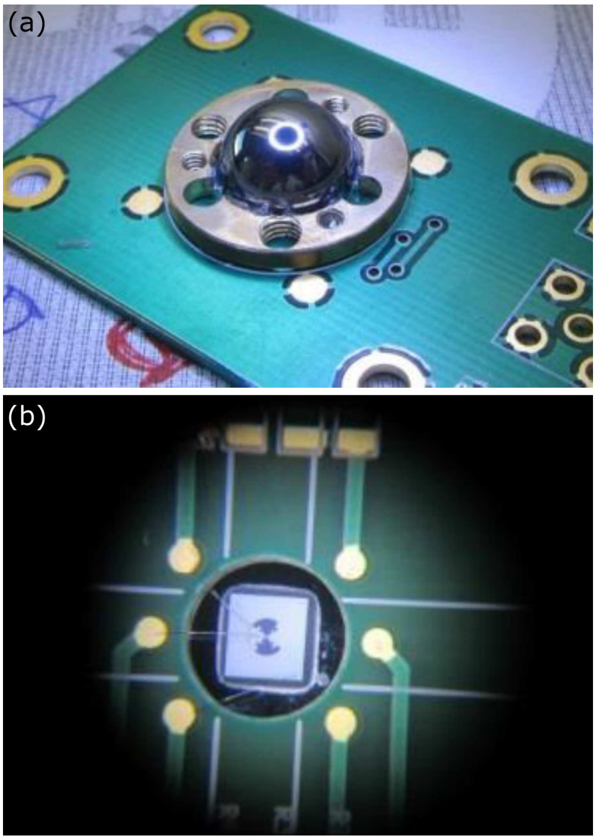

Fig. 5. Picture of a THz detector integrated with log-periodic antenna assembled on a PCB with Si-lens fixed: (a) view from top of PCB, (b) view from backside of PCB.

The results demonstrate a significant increase in the detectivity of the HR Si detectors with modified CS layout. An essential advantage of the proposed technology is its full compatibility with use of HR Si lenses that may be assembled directly underneath the chip. Detectors integrated with antenna and equipped with lenses form a new family of THz devices that might be suitable for communication.

Using the process described in the paper, we fabricated the detector integrated with a Si-HR lens and with a wide-band log-periodic antenna receiving the THz radiation through the entire substrate — Fig. 5. In this case there was no need to design the detector on a thin membrane (both, lens and substrate are of HR-Si), so the manufacturing was simpler. Comparing to a narrow-band detector using an array of two patch antennas, the log-periodic wideband detector assembled with use of hyper-hemispherical HR silicon lens of 10 mm diameter exhibited the gain of 16–20 dB over wide band.

5. Summary

Following our investigations several modifications of THz detector technology have been proposed. The process allows to manufacture detectors on the high resistive bulk wafers. The most important achievement of the reported work was a change of the design rules concerning the layout of the channel stoppers in the vicinity of the antennas. This modification significantly increased the sensitivity of the detectors. The high resistivity silicon substrates allowed for the integration of the field effect based detectors with the silicon lenses.

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