CMOS-compatible Si-TiN Schottky SWIR photodetectors enhanced by pyramidal nanostructures

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Abstract—Short-wavelength infrared detection has shown an enormous potential for future application in autonomous systems and security. Up to today the use has been limited by the cost for high quality detectors. Using TiN Schottky barrier photodetectors with pyramidal photonic nanostructures opens a path to circumvent the typically low quantum efficiencies with compatibility to CMOS technology.

Keywords—Photodetector, Schottky barrier, short-wavelength infrared, CMOS technology, Nanophotonics

I. INTRODUCTION

Short-wavelength infrared (SWIR) photodetectors have long been used in telecommunications and nowadays reach out as focal plane arrays (FPA) into applications for autonomous vehicles, security, and quality assurance [1]. There, the increased wavelength starting from 1 and ranging up to 3 µm helps to clear up scenarios obstructed by fog, or allows to assure the quality of products wrapped in packaging. As advantageous as this technology is for future automation of processes the hurdles to take are still high. The common detector technology relies on compound semiconductors like III-V materials which have unprecedented quantum efficiency. Due to their technological incompatibility with typically used Si-processes for CMOS read-out circuitry a complex process of stacking the detector chip and read-out circuitry is necessary. Therefore, the production of III-V focal plane arrays has not seen the intense scaling which occurred in CMOS production and brought prices for visible radiation focal plane arrays down.

II. SI SWIR DETECTION

A inter band detection of SWIR radiation in Si is not possible as the band gap avoids the generation of electron-hole pairs for wavelength above the cut-off wavelength of ~ 1.1 µm. In order to facilitate the generation of charge carriers above that wavelength, non-linear processes, inter band gap states or Schottky barriers can be used [2]. Due to the demanded high electric fields the first is technically unsuited for FPAs. The introduction of inter band gap states demands for complex doping processes wherefore Schottky barriers are technologically the easiest possible way to achieve SWIR detection using a metal semiconductor interface. The radiation excites “hot” charge carriers which potentially could overcome the Schottky barrier. A drawback of these devices is a low quantum efficiency, high reflectivity, and high noise currents, why they usually used in an actively cooled setup [3].

III. IMPROVING SCHOTTKY BARRIER PHOTODETECTORS

The responsivity of a backside illuminated detectors is defined by

\[ R_{\text{opt}} = (1 - R_{\text{BS}})(1 - R_{\text{Device}}) \eta_{\text{IQE}} \frac{e}{E_{\text{photon}}} \]

Here, \( R_{\text{BS}} \) is the reflection from the wafer backside, \( R_{\text{Device}} \) is the reflection from the device interface, \( \eta_{\text{IQE}} \) is the internal quantum efficiency (IQE), \( e \) is the elementary charge and \( E_{\text{photon}} \) the energy of one photon. Expect for \( e \) all physical quantities are functions of the wavelength. To increase absorption (and reduce reflectivity) of the device, photonic nanostructures like distributed bragg setups [4], plasmonic structures or pyramidal setups have been incorporated along the detectors interface. There has been significant hope to improve hot charge carrier generation using plasmonic nanostructures which have so far not been met [5]. Pyramidal structures on the other hand enable funneling of radiation into the tip’s confined space, thereby increasing the electric field strength in this volume and increasing responsivity. This does not only enhance the generation of hot charge carriers but also allows to reduce metallized surface and limit dark currents [6]. Dark currents are an issue of interface states and thermally excited carriers which overcome the barrier. While the first can by contained by the process technology the latter is directly correlated to the height of the Schottky barrier. A trade-off for an uncooled device is a barrier height of 0.6 eV which correlates to ~ 2 µm wavelength. Increasing the internal quantum efficiency is by far the most potent factor for enhancing responsivity. Through materials with a reduced density of states around the Fermi level [7] and thin metal layers significant improvements are expected or have been shown recently [8].

Fig. 1 a) Scanning electron microscopy image of the Si nanopyramids after etching. b) Schematic crosscut of the device.

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IV. RESULTS AND DISCUSSION

The device design combines nanophotonic pyramidal structures with a TiN Schottky contact on a p-Si substrate. Compared to the wet-etching processes used typically, the arrays of pyramidal structures are created by a double step anisotropic-isotropic dry etching process (see Fig. 1a) to maintain CMOS compatibility. The ohmic substrate contact is a p'-region. Contacts are created by a sputtered 500 nm AlSiCu on top of the 5, 10 or 20 nm sputtered TiN layer. To evaluate the improvement of the pyramidal nanostructure plane reference devices where created which are comparable to literature. Next to wafer scale electrical characteristics the responsivity was determined by homogenous and stepwise illumination from the back with small bandwidth radiation (< 2.5 nm).

A. TiN Schottky Barrier

The plane reference devices have shown a close to ideal diode behavior. Independently of the TiN layer thickness and the backward voltage a saturation current of < 1 μA/cm² is observable. Together with an ideality < 1.05 that implies a nearly perfect interface. From \( I(U, T) \) measurements using the Richardson plot a barrier height of 0.6 eV was found, which meets the expectations (see Fig. 2).

B. Nanopyramidal Structures

The nanophotonic structure creates a complex wavelength dependent interaction of the irradiation with reflections and plasmonic resonances within the pyramid. It is expected that some of these interactions lead to a funneling of radiation into the pyramids tip, creating there a volume of enhanced electric field strength. Therefore, introducing the nanostructures has a clear influence on the device responsivity. The dry-etching process allows to alter slope, plateau width and distance between the single pyramids in the matrix. Structures of any kind let to an improvement in responsivity. Within the evaluated parameter set the pyramids with reduced spacing and increased plateau width had an improvement by a factor of 2000 compared to a plane reference on the same sample.

REFERENCES