Solar-Blind Dual-Band UV/IR Photodetectors Integrated on a Single Chip

D. Starikov [a,b,*], C. Boney [a,b], R. Pillai[b] and A. Bensaoula [b]

[a] Integrated Micro Sensors, Inc., 10814 Atwell Dr, Houston Tx 77096, USA, dstarikov@imsensors.com
[b] Texas Center for Advanced Materials, University of Houston, 724 S&R Building 1, Houston, Tx 77004, USA, bens@uh.edu

ABSTRACT

Employment of layered structures made of semiconductor materials with different optical absorption bands, is a new way of realizing either a broad spectrum photodetector or selective multiple band photodetectors. Such a concept based on structures fabricated using stacked semiconducting layers to obtain a multi spectral photoresponse is investigated in this paper. Based on the selected approach, fabrication of a dual-band UV/IR photodetector with a reasonable responsivity at room temperature has been demonstrated. The integrated device is capable of detecting optical emissions separately in the UV and IR parts of the spectrum. The responsivities of this device are ~0.01A/W, at a peak wavelength of 300 nm and ~0.08 A/W, at a peak wavelength of 1000 nm, respectively. The described dual-band photodetectors can be employed for false alarm-free fire/flame detection and advanced hazardous object or target detection and recognition in several industrial, military, and space applications.

Keywords: ultraviolet, infrared, photodetector, silicon, III nitrides

1. INTRODUCTION

Solid-state optical detectors, based on semiconductor materials, have replaced photoemissive devices in a wide variety of both commercial and military applications due to their broad spectral responsivity, excellent linearity, high quantum efficiency, large dynamic range of operation, and high potential for integration into large-format image arrays [1].

The spectral range of most semiconductor-based optical detectors is determined by optical absorption in the active semiconductor material layer at energies above the semiconductor band gap. As a result, narrow-band gap semiconductors, such as II-VI compounds in particular HgCdTe, are suitable for infrared detection. Si and some III-V compounds are perfect for detection in the visible (VIS) and near infrared (IR) range, and wide band gap semiconductor materials, such as diamond, SiC, and III nitrides, are superior for applications in the ultraviolet (UV) range.

Several military and industrial applications require simultaneous (or at least spatially registered/synchronized) detection of optical emissions in different spectral regions. Many such applications involve detection of flames, fires, and explosions that produce emissions in a wide range of the optical spectrum. Such emissions have distinct sharp peaks in both UV and IR that can be differentiated over the wide spectral range ambient light background by high-resolution, fast optical detectors, allowing time-resolved measurements in multiple spectral bands.

Multi-band detection capability featured in a single chip device became possible due to recent developments in the growth and processing of new semiconductor materials used for various spectral bands. Significant progress has been made lately in the development of UV detectors based on wide band gap materials. Several attempts to develop UV detector structures on diamond [2] were made by 1996, but due to the lack of high quality layers and insufficient doping levels, they did not result in practical devices. Visible-blind UV photodetectors have been fabricated on Silicon Carbide (SiC) substrates [3, 4], but the technology is relatively immature due to the lack of high quality large area substrates until few years ago (and no large area substrates prior to 1989 [1]).

Group III nitride materials are superior for advanced UV detector fabrication due to their wide direct band gap and high thermal, chemical, mechanical, and radiation tolerance. A large amount of research has been dedicated lately to the development of UV detectors based on GaN [5-7], GaN/AlGaN [8-10], and AlGaN [11]. Currently, attracting the most interest are AlGaN-based structures since they can allow detection in the very important UV range of 240-280 nm, which corresponds to the absorption range of solar radiation by the ozone layer [1].

In the area of IR detection, the conventional HgCdTe- and InSb-based detectors display high quantum efficiencies but are difficult to integrate into large arrays [1]. Detectors based on heterointernal photoemission (HIP) in Ge_xSi_{1-x}/Si heterojunctions have demonstrated additional opportunities for integration on Si wafers at sufficient sensitivities in the infrared range of 1-12 μm [12-15]. Large area SiGe-based HIP photodetector arrays of 400x400 pixels have been available for close to ten years [16].

Recent work on photodetector structures based on metal silicides [17, 18] has positively shown possibilities to extend the silicon-based detector's spectral range further into IR. However, such devices are limited to operation under cooled conditions, such as cryogenic temperatures or even lower.

The opportunity to grow III nitrides on Si wafers can be considered as the main key to the development of integrated multi-color detectors ranging from the UV to IR. Device-quality GaN layers have been demonstrated lately by several groups [19-24]. The new challenge is the growth of high quality InGaN and AlGaN layers on Si wafers in order to fabricate optoelectronic devices working in the range from UV to IR. Such an approach, based on stacked UV and IR pixels, removes the important fundamental problem of spatial alignment in multi wavelength array detectors.

In this work, we will demonstrate fabrication and characterization of a UV/IR visible-blind photodetector based on stacked semiconducting layers with desired properties, integrated on a single chip. The fabrication of the device is based on the growth of III-Nitride compounds on commercial Si wafers by Radio-Frequency Molecular Beam Epitaxy (RF MBE), which allows for precise control over the layer quality and composition at relatively high (up to 2 µm/hr) growth rates. In addition, employment of MBE allows for simple integration of molecular sources that can be used to grow III nitride compounds such as InN, GaN, InGaN, AlGaN, and AlN. Depending on the incorporation of In and Al in these compounds, the band gap of the epitaxial layer can be theoretically varied from about 0.8 eV (band gap of InN) to about 6.2 eV (band gap of AlN) [25]. MBE is also currently the method of choice for the fabrication of Si and SiGe based device heterostructures.

2. DEVICE LAYOUT

There are many approaches to employing stacked semiconducting layers in order to build multi-band photodetectors. In this work we focus on dual-band visible or solar-blind structures with sensitivities separately in the UV and IR parts of the spectrum.

Our approach is based on employment of III nitride layers grown on Si for fabrication of the UV-sensitive photodiode structures on the front side, and fabrication of the Si- or silicide-based IR-sensitive photodiode structures on the backside of commercial Si wafers. In this case the Si wafer also serves as a filter to visible light (Figure 1). The advantages of this approach include the relatively low cost and the availability of double side-polished Si substrates optimized for photodiode structure fabrication, while the drawbacks are the high lattice mismatch with the III nitride layers resulting in less than ideal crystalline quality, as well as

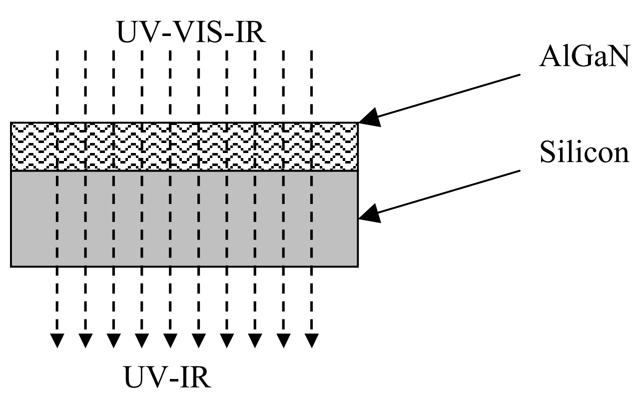

Figure 1: Approach based on a III nitride layer stacked on Si, and using the absorption properties of Si to filter out visible radiation.

the difficulties related to handling and processing of thin or even ultra-thin Si wafers that might be needed to optimize the IR radiation transmission and visible light blockage device characteristics.

3. EXPERIMENTAL REULTS

The UV/IR Photodiode structure, fabricated on a single chip, is shown in Figure 2. All III-nitride layers used for the photodiode fabrication were grown in a custom-made MBE chamber equipped with standard effusion cells for the group III components, such as: Ga, Al, In; and dopants, such as: Si, and Mg. Active nitrogen species are generated by an EPI Uni-Bulb radio-frequency (RF) plasma source. The details related to the III nitride growth and Schottky barrier formation are described in our previous publications [26-28].

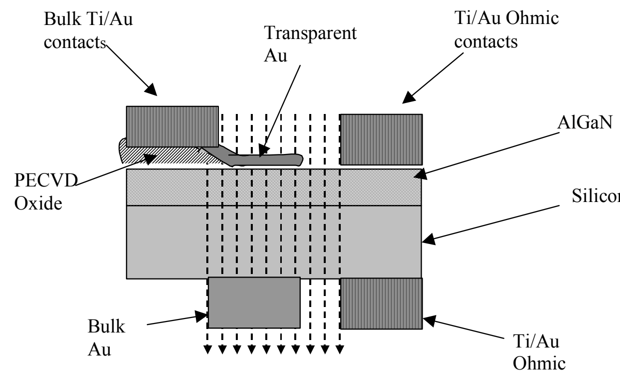

Figure 2: Schematic showing the processed dual structure chip with aligned Schottky and ohmic contacts on the front side and the backside.

In the present work the film growth experiments were carried out on commercial-grade 2” diameter thin (175 µm) Si <111> wafers. After the AlN buffer layer growth, the substrate temperature was lowered for the deposition of GaN. The GaN film was deposited at 700 ºC, in order to strike a balance between film quality and background n-type doping, arising from Si diffusion out of the substrate. Interspersed in the 1.55µm of GaN were 3 thin (~10 nm) AlN layers deposited at a lower temperature and used to reduce stress in the film and hopefully reduce cracking of the final layers. We nevertheless observed a slight curvature of the resulting wafer as a result of the stress built up during the growth process and the use of a relatively thin silicon wafer.

Formation of Schottky barrier structures on n-GaN layers was started by a Plasma Enhanced CVD (PECVD) deposition of a 2µm thick tapered silicon oxi-nitride layer in order to provide continuity and isolation for a thin (100-200 Å) semi-transparent 1 mm diameter Au contacts. These contacts were deposited by thermal evaporation through a stencil mask partially on GaN surface and partially on the tapered oxide layer as shown in Figure 2. A thicker (2000 Å) Au contact deposited by e-beam evaporation was used also to form a Schottky barrier on the back side of the Si wafer. The ohmic contacts for both Schottky barrier structures and the semi-transparent Au layer sitting on the tapered oxide were formed by e-beam evaporation of Ti/Au (1000Å/1000Å) layers.

After fabrication of the Schottky barrier and ohmic contacts on both sides of the substrate, the sample was diced into smaller chips each having a single dual-band photodetector structure composed of 2 Schottky and 2 ohmic contacts on each side. The chips were then mounted onto insulating AlN ceramic plates that provide comparatively high thermal conductivity. Prior to chip attachment, the AlN plates were diced and a 5000 Å thick Au layer was deposited on one of the AlN ceramic plate sides by electron beam evaporation. The Au layer was then patterned using photolithography to match Schottky and ohmic contacts on the backside of the photodetector chip. The chips were then bonded to the patterned Au contacts on the AlN plate using a silver based high temperature electrically conductive resin and gel-type glue for improving the bonding strength and providing isolation between the Schottky and ohmic contacts. The metallization pads were then bonded to the TO-8 housing pins. Figure 3 shows a fully functional dual-band photodetector device packaged into a standard TO-8 housing.

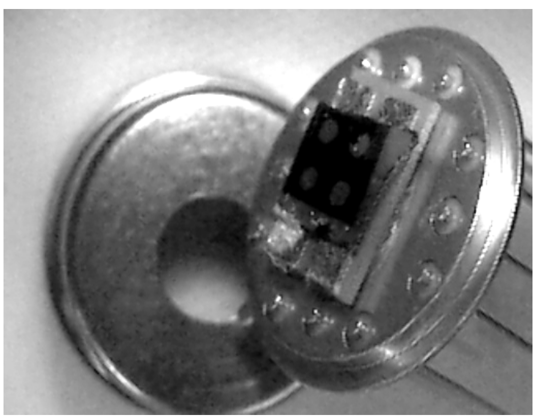

Figure 3: Packaged integrated UV/IR photodetector prototype.

Spectral response measurements from the packaged photodetector were performed using an automated Jobin Yvon Triax 320 spectrometer. A calibrated xenon lamp was used for measurements in the UV and visible ranges; and a tungsten filament calibration lamp was used for measurements in the near and mid IR range.

The spectral response measured in two separate bands (Figure 4) indicates reasonable spectral selectivity of the device in the UV and the near IR bands. The peak responsivities at wavelengths of 265 nm in the UV and 1000 nm in the IR measured using an Oriel optical power meter at fixed values of the incident light power densities, were ~0.01 A/W (AlGaN-based structure) and ~0.08 A/W (Si-based structure), respectively.

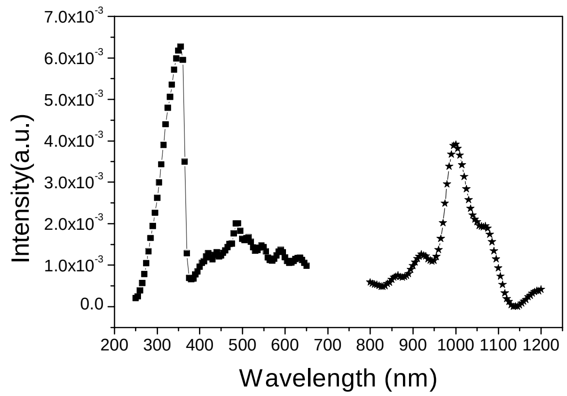

Figure 4: Spectral response from the dual band integrated photodetector measured separately in the UV and IR bands.

4. CONCLUSIONS

A viable approach to fabricating a dual-band UV/IR photodetector integrated on a single chip has been selected among various possible concepts that can be considered in the future. This concept based on employment of III nitride layers grown on commercial Si wafers was realized in an experimental visible-blind UV/IR photodetector operating at room temperature. The device was packaged into standard TO-8 housing and exhibited reasonable peak responsivities separately in the UV and IR parts of the spectrum.

Further improvements in the device performance can be achieved by optimization of the diode junctions, used in the photodetector fabrication. For example, replacement of Schottky barriers with p-i-n junctions might result in higher efficiencies.

The spectral response of such devices can be also improved by better separation of the UV and IR bands resulting in solar-blind devices and extension of the sensitivity further into the UV and IR bands. This can be achieved by optimization of the Si layer thickness and introduction of AlGaN layers with higher (more than 50%) Al content and replacement of Si-based junctions with silicide-based ones.

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