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Micro-transfer printed InGaAs photodetector on SOI platform

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***Abstract*—Transfer-printed InGaAs photodetectors are integrated on SOI by evanescent, grating and edge coupling, exhibiting responsivities of 0.7, 0.38 and 0.15 A/W, with dark currents of 48, 47 and 400 nA at 0.6 V reverse bias respectively.**

Keywords—Photodetector, InGaAs, Transfer printing, heterogeneous integration.

I. INTRODUCTION

Si photonics has been explored over last two decades, and promises to become a mainstream technology for photonic integrated circuits operating in the 1300 nm – 1600 nm wavelength range [1,2]. Photodetection requires the integration of another material. The indirect semiconductor Ge [3] has become the choice at foundries but its integration involves a complex high temperature fabrication process. On the other hand, InGaAs photodetectors (PD) have been the mainstay in communication systems with high responsivity and high bandwidth. Thus far, integration of InGaAs photodetectors on the silicon-on-insulator (SOI) platform have been demonstrated by epitaxial growth [4] and by wafer bonding [5] techniques. An alternative strategy is to integrate the PDs by micro-transfer printing [6] which has many advantages in terms of highly efficient material usage and low process temperature. In this paper, we report on the preparation and transfer printing of InGaAs uni-travelling carrier (UTC) PDs to 500 nm thick SOI platform, through evanescent, grating and edge coupling. At 1550 nm and -0.6 V bias, we report responsivity of 0.7, 0.38 and 0.15 A/W along with dark currents of 48, 47 and 400 nA respectively.

II. DESIGN AND FABRICATION

Fig. 1a, shows the UTC-PD epitaxial stack grown lattice-matched on an InP substrate by metal organic chemical vapour deposition. The design consists of a 400 nm absorbing InGaAs layer, to match with the 500 nm Si waveguide, in order to obtain high optical coupling in edge coupled PD. The electrons generated are prevented from reaching the p-type contact by wider bandgap InGaAsP blocking layer and thus they diffuse towards the 150 nm thick n-type InP. The holes are majority carriers and are assisted to the p-type contact by graded bandgap layers. Since electrons are the only moving carriers, this UTC [7] design enables high bandwidth. A 400 nm InGaAs and 100 nm AlInAs dual sacrificial layer [8] is employed for the device releasing process.

Photodetectors of size 19 µm x 55 µm are fabricated on the InP substrate in the following sequence: 1. Ti/Pt/Au p-metal deposition, 2. p-mesa etch to N-InP, 3. Au/Ge/Au/Ni/Au n-metal deposition on n-InP, 4. PD coupon definition, 5. SiN encapsulation of active layer and 6. Photoresist tether definition (Fig. 1b) followed by undercut of sacrificial layers at room temperature for 5 min using $FeCl_3$:H_2O (1:2), to release the PDs from the substrate. The 675 nm ultrathin PDs are directly bonded to SOI wafer by transfer printing. Bonding

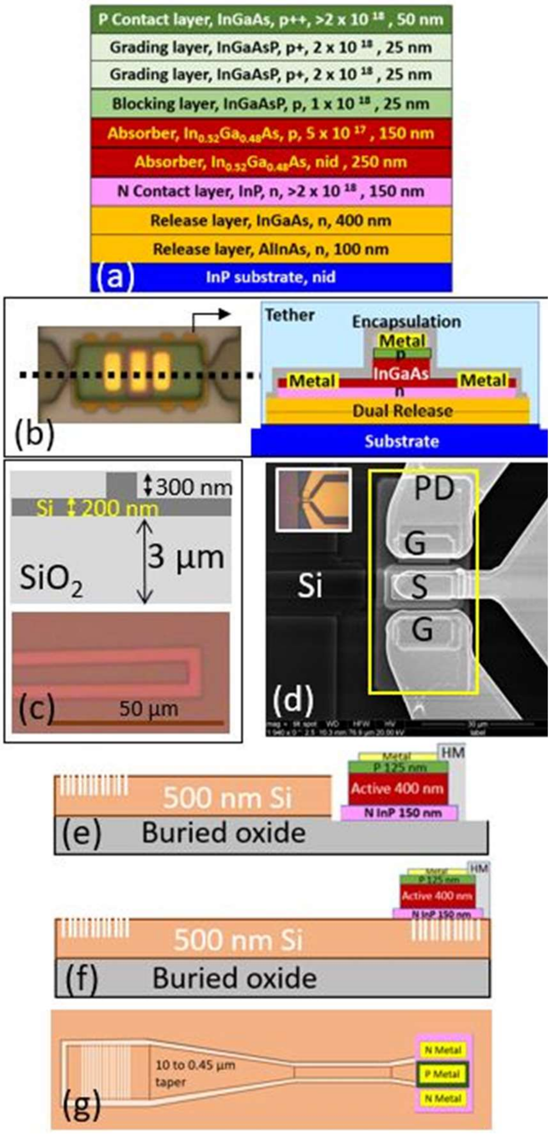

Fig. 1. Epitaxial layer structure (a), microscope image and cross section of photodetector coupon (b), rib etched Si waveguide cross section and top view (c), scanning electron microscope image of integrated PD, microscope image inset (d), schematic representation of transfer print PD: edge (e), grating (f) and evanescent (g) coupled PD.

without adhesives is achieved due to the smooth coupon interface with measured roughness of 0.2 nm over 10 µm x 10 µm area obtained as a result of dual release layer.

The SOI wafer has 500 nm Si with 3 µm buried oxide. Patterns on Si are created by a rib etch of 300 nm for 5 µm width around as shown in Fig. 1c, microscope top view image. This pre-patterned SOI wafer is obtained from Cornerstone, consisting of grating couplers, which are 160 nm ± 15 nm etched, tapers of 10 µm to 450 nm wide waveguides designed to couple TE mode at 1550 nm. The same device types are printed for edge coupling at the waveguide end, for grating coupling directly on the output grating and directly on the waveguide for evanescent coupling as illustrated in Fig. 1e-g. After printing, a thin 50 nm SiO_2 is deposited on SOI wafer to hold the coupon intact for further integration process steps on the SOI wafer. Finally, the metal contacts on PDs are opened and connected to Ti/Au bond pads for RF probing (Fig. 1d).

III. RESULTS AND DISCUSSION

To calculate the responsivity of UTC-PD, the power coupled to the waveguide is estimated using reference grating couplers which are placed close to the actual device. The setup for testing grating couplers is similar to Fig. 2a, except on the output side, instead of the PD, the light is measured using power meter from output grating coupler. They have an efficiency of -6 dB per coupler at 1550 nm as plotted in Fig. 2b. The photodetector is characterized at room temperature using setup in Fig. 1a, with a 1550 nm source sent through a polarization controller to input grating coupler. The measurements from the PD are made using electrical contact probes and voltage-current source meter. The inset is a photograph of the chip during measurement with optical fiber and metal probes seen. Fig. 2c shows the dark currents of evanescent and grating coupling to be <50 nA while the edge coupled device has 400 nA at 0.6 V reverse bias. After the input grating coupler, power of 0.54, 0.8 and 1.1 mW is supplied to the PD whose reverse bias characteristics are shown in Fig. 2d-f for different coupling mechanism. The corresponding responsivity and quantum efficiency are plotted in Fig. 2g, where the increase in responsivity can be due to a higher surface area (17 µm x 7 µm) for the PD in evanescent and grating coupling compared to the side area of (400 nm x 7 µm) in the edge coupled device.

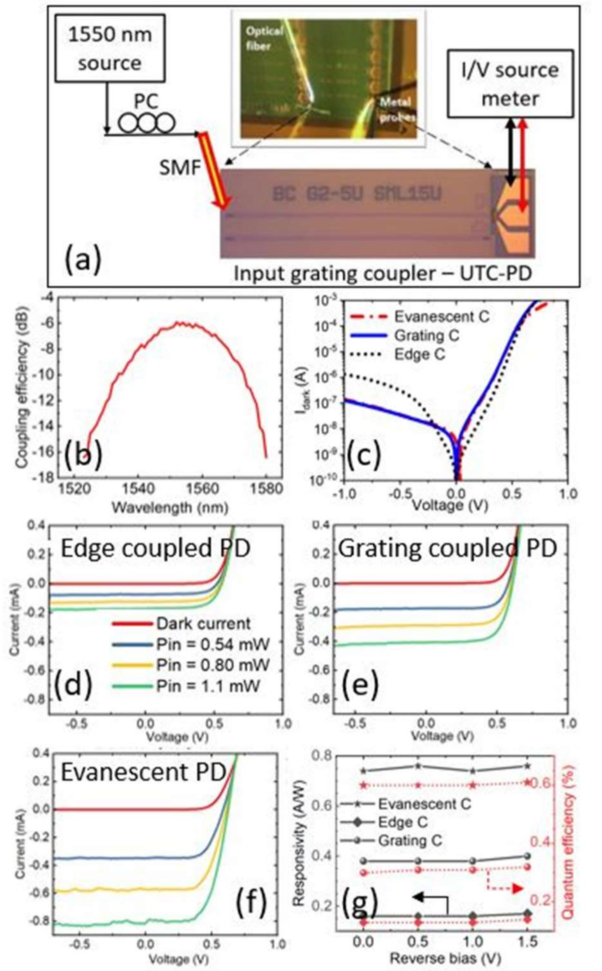

Fig. 2. Schematic measurement setup (a), plot of grating coupler efficiency (b), measured dark currents (c), reverse bias characteristics under illumination with 1550 nm light of edge (d), grating (e) and evanescently (f) coupled PD and responsivity and quantum efficiency of PDs (g).

IV. CONCLUSION

The UTC-PD is successfully fabricated and DC testing is presented, with high speed measurements to be completed. This article demonstrates the effective use of transfer print technique to integrate the same PD type by three coupling mechanisms, without involving any high temperature process or regrowth.

ACKNOWLEDGMENT

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