Embedded optical interconnections using thin film InGaAs metal-semiconductor-metal photodetectors

Z. Huang, Y. Ueno, K. Kaneko, N.M. Jokerst and S. Tanahashi

The integration of InGaAs photodetectors embedded in a polymer interconnection waveguide on Si and ceramic electrical interconnection substrates has been demonstrated. The photodetector and substrate are independently fabricated and bonded, with subsequent waveguide integration. The embedding fabrication process, coupling, and bandwidth are reported at 1 Gbit/s.

Introduction: Ultra-short-haul optical interconnect, in the 'milli-haul' range, is a promising solution for the projected electrical interconnection limitations identified by the Semiconductor Industry Association Roadmap. These optical interconnections can address electrical interconnection limitations such as skew, and may offer simpler interconnect design and alternative architectures [1]. Milli-haul optical interconnections can be integrated to effectively address electrical interconnection limitations implemented either in a system on a chip (SOC) or in a system on a package (SOP) configuration, with the latter occurring at the substrate, board, or backplane level.

Research into milli-haul optical interconnections at the substrate and board levels is beginning to emerge, and examples include polymer waveguide optical interconnects on GaAs substrates using GaAs metal-semiconductor-metal (MSM) photodetectors (PDs) [2], and a Si substrate with Si PDs and polymer waveguides [3, 4]. All of these papers use the same material for the substrate and the PD. In contrast, in the work described in this Letter, thin film InGaAs MSM PDs are separately grown, fabricated, and bonded to Si or ceramic interconnection substrates for embedded waveguide interconnection. Thus, the PDs are optimised independently of the interconnection substrate, and limitations associated with monomaterial integration of the PD in the substrate material can be avoided with this heterogeneous integration process, including the use of non-semiconductor substrates, such as ceramics and polymers, and 1.3 and 1.55 μm wavelengths, which Si and GaAs do not detect efficiently. After the bonding of the PD to the host substrate has been completed, waveguides are deposited and defined on top of the PDs to create waveguide optical interconnections on the host substrate. Thus, in this Letter, thin film InGaAs-based PDs embedded in polymer optical interconnection waveguides integrated onto ceramic and silicon substrates are reported. It is projected that future aggregate optical interconnection rates in excess of 100 Tbit/s can be realised using the integration approach of embedded PDs in waveguides described herein.

Devices and integration: The PDs which are separately grown and fabricated with subsequent bonding to the host substrate are thin film inverted MSM PDs. An inverted MSM (I-MSM) is a PD which eliminates MSM responsivity degradation due to finger shadowing by locating the fingers on the bottom of the device and removing the growth substrate. This results in a high responsivity (comparable to a PiN) for the same absorbing layer thickness [5], therefore these thin film I-MSM PDs are ideal candidates for embedded PDs which detect an evanescently coupled optical signal from the waveguide. The I-MSM PD is bonded with the metal fingers facing the substrate (Si and ceramic reported herein), with subsequent deposition and patterning of the waveguide over the I-MSM to embed the PD in the waveguide.

The I-MSM is independently grown and fabricated, and bonded to an SiO_2-coated Si (SiO_2/Si) or ceramic substrate. The as-grown MSM consists of: InP (substrate)/200 nm $In_{0.53}Ga_{0.47}As$ (stop etch layer)/40 nm InAlAs composition graded to 740 nm $In_{0.53}Ga_{0.47}As$ (absorbing layer)/40 nm InAlAs composition graded to 40 nm InAlAs (cap layer to reduce dark current). The MSM PD is 200 × 200 μm square with 2/2 μm finger and spacing and two 40 × 200 μm contact pads. The metal electrodes are Ti (30 nm)/Pt (50 nm)/Au (250 nm). The MSM mesas are defined using a citric acid: H_2O_2 (10:1) wet etch to the stop-etch InGaAs layer. Apiezon W is used to protect the top surface during the InP substrate wet etch removal using $HCl{:}H_3PO_4$ (1:1) at 50°C. Next, the I-MSMs are bonded to a transparent transfer medium, the Apiezon W is removed using TCE, and the thin film MSM PDs (individually, or in arrays) are bonded to Ti (100 nm)/Pt (50 nm)/Au (500 nm) metal pads on the SiO_2/Si or ceramic host substrate. The I-MSM metal electrodes are facing the substrate metal pads when the I-MSMs are bonded, resulting in a stable metal/metal bond. The final I-MSM integration step is an anneal at 270°C for 30 min.

Siloxane polymer waveguides with embedded InGaAs thin film I-MSMs have been integrated onto both SiO_2/Si and ceramic substrates. After the I-MSM has been bonded to the substrate, the siloxane waveguide core and cladding are spin coated onto the substrate and the core is defined into a channel waveguide. First, a 10 μm-thick siloxane oligomer under cladding is spin coated onto the substrate and cured at 270°C in N_2 for 1 h. This undercladding layer is then etched back to approximately 1.5 μm thick, and is followed by a 7 μm-thick TiO_2-doped siloxane oligomer core and cured. The singlemode core is then defined into a 7 μm-wide channel (over the PD) using an Al mask and reactive ion etch with O_2/CF_4. The Al mask is then removed, an upper clad coat of 12 μm of siloxane oligomer is applied, and a final cure at 270°C in N_2 for 1 h and removal of the polymer from the contact pads completes the waveguide integration process. Fig. 1 is a photomicrograph of a siloxane waveguide with an embedded I-MSM PD.

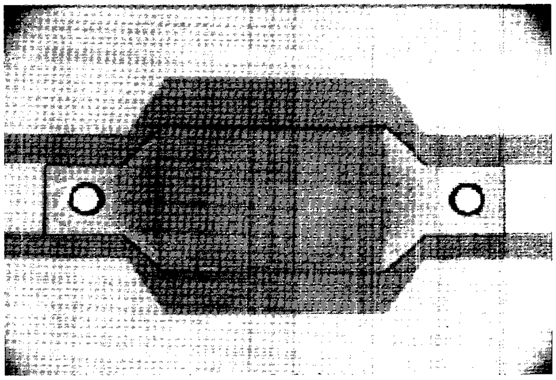

Fig. 1 *I-MSM PD, 200 × 200 μm, embedded in polymer waveguide on SiO_2/Si substrate*

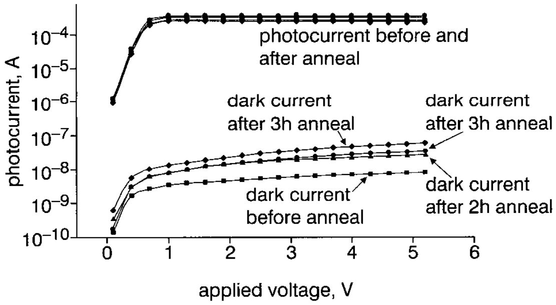

Fig. 2 *DC characteristics of I-MSM PD against anneal time at 270°C, at bias 0–5.2 V*

Testing results and analysis: Since MSMs are Schottky contact devices, they are sensitive to thermal processes such as those used to cure the waveguide under which the I-MSM is embedded. Dark current measurements which are conducted on I-MSMs that have been annealed for 3 h at 270°C (the same as the siloxane waveguide fabrication process), are shown in Fig. 2 for a bias from 0 to 5.2 V. The dark current rises significantly after the first hour of anneal, with a continuous bake for another hour, the dark current decreases, and then rises again to 34.2 nA at 5 V after another hour of annealing (for a total 3 h anneal). These results are consistent with I-MSM dark currents measured in embedded waveguides, which, for the same device runs for the data above, result in an embedded PD dark current of 42.8 nA. Although it has not been demonstrated herein, the metallisation for I-MSMs can be designed to produce lower dark current after low temperature anneals [6], and thus, this fluctuation in dark current for embedded PDs is not an inherent integration performance limitation.

The optical signal is evanescently coupled from the waveguide into the embedded PD. The refractive index of the siloxane waveguide core and cladding are 1.450 and 1.455, respectively. Using 3D beam propagation (BPM) simulation, the coupling efficiency from the waveguide to the I-MSM is theoretically calculated to be 7%. The coupling efficiency has also been roughly estimated through measurement. To measure the coupling into the embedded I-MSM, a DFB laser at a wavelength of 1310 nm was coupled into a singlemode fibre (core diameter 9.5 μm) which was aligned to one end of the waveguide. The I-MSM photocurrent was monitored to optimise fibre to waveguide endface alignment. When the mode was guided, a sharp photocurrent peak was observed, whereas side cladding modes had multiple soft peaks as the fibre was scanned across the waveguide endface. At 1 Gbit/s, the average input power from the fibre was 0.40 mW, producing 0.80 μA of output current from the I-MSM. The estimated coupling from the fibre to the waveguide is 90%, however the waveguide loss in this experiment was unusually (for this material) high, resulting in a total (coupling and propagation loss) of 8 dB from the fibre to the I-MSM. Thus the incident optical power on the I-MSM was 64.6 μW. Using the 0.42 A/W I-MSM responsivity, and ignoring reflections, a worst-case estimate of the evanescent coupling efficiency is approximately 2.9%.

In addition to coupling measurements, eye diagrams have been measured on both ceramic and SiO_2-coated Si substrates for embedded I-MSM PDs. The eye pattern of evanescently coupled light from waveguides into I-MSMs on both SiO_2/Si and ceramic substrates yields an open eye at 1 Gbit/s. Fig. 3 shows the eye pattern for an embedded I-MSM on a ceramic substrate at a PRBS of $2^7 - 1$.

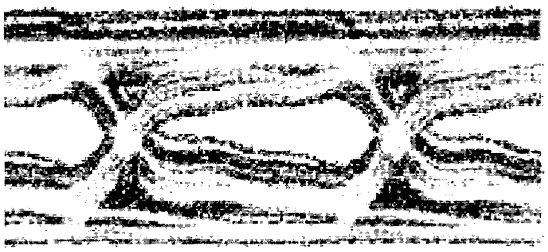

Fig. 3 *Eye pattern of waveguide embedded I-MSM on ceramic substrate for 1 Gbit/s optical input signal*

Conclusions: Optical coupling from a polymer waveguide into a thin film embedded photodetector has been demonstrated on SiO_2/Si and ceramic substrates. These thin film PDs are InGaAs-based I-MSM photodetectors which have been independently optimised separately from the waveguide and substrate. Coupling from the waveguide to the embedded photodetector has been demonstrated, and an eye diagram at 1 Gbit/s for this interconnection has been presented. This initial demonstration of embedded integrated interconnection is a first step towards high aggregate bandwidth embedded optical interconnections on substrates, boards, and backplanes.

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High DC power 325 nm emission deep UV LEDs over sapphire

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Flip-chip 325 nm emission LEDs over sapphire with powers of 0.84 and 6.68 mW at 180 mA DC and 1 A pulsed pump currents are reported. A thermal management study shows the DC output power to be limited by the package heat dissipation.

There have been a number of reports recently of deep ultraviolet (UV) (280 nm < λ < 350 nm) III-N quantum well light-emitting diodes (LEDs) on sapphire, SiC and bulk GaN substrates [1–5]. In these substrate choices, conducting SiC and HVPE GaN have superior thermal conductivity and they also allow for a vertical conduction device geometry. However, they are highly absorbing in the deep UV wavelength region and thus require the output power extraction through the top *p*-contact and the p^+-GaN contact layer side. In contrast, we have shown sapphire to be a good substrate choice for deep UV LEDs as it allows for an efficient light extraction through the substrate side [3, 4]. However, due to low thermal conductivity and the relatively high device operating voltages, sapphire substrate-based deep UV LEDs suffer from excessive self-heating in the DC operation [6]. Using micro-Raman spectroscopy with 325 nm emission deep UV LEDs, we recently estimated the self-heating related device temperature rise to be about 70°C for a DC bias current of 50 mA [7]. Now, with flip-chip packaging in a customised silver (Ag) plated copper header, we report record DC and pulsed powers of 0.84 and 6.68 mW for room-temperature operation of 325 nm LEDs over sapphire. The DC power increased to 1.5 mW when packages were cooled down to 10°C.

The epilayer structure of the 325 nm LEDs described in this Letter was grown over basal plane sapphire substrates using low-pressure metal organic chemical vapour deposition (LP-MOCVD). Similar to our previous report [4], a 10-period AlN (20 Å)/$Al_{0.2}Ga_{0.8}N$ (300 Å) superlattice (SL) and a 2 μm-thick n^+-$Al_{0.2}Ga_{0.8}N$ layer were used for the buffer and the bottom *n*-contact layers. The device active layer consisted of three $Al_{0.18}Ga_{0.82}N$ (110 Å)/$Al_{0.12}Ga_{0.88}N$ (35 Å) quantum wells. These were capped with a 200 Å-thick Mg-doped *p*-$Al_{0.3}Ga_{0.7}N$ and a 500 Å-thick p^+-GaN layer. 200 × 200 μm square geometry mesa devices were then fabricated. The mesa etching and contact metalisation and annealing procedures were identical to those reported earlier [4, 7].

The fabricated wafer was then diced and single chips were mounted in a flip-chip configuration on high thermal conductivity (175 W/mK) insulating AlN carriers by thermo-compression gold bonding. The AlN carriers with the flip-chip LEDs were then attached to 16 mm-diameter silver-coated copper headers. In addition, a parallel combination of four 200 × 200 μm LEDs was also flip-chip mounted on similar copper headers. In further discussion we refer to this configuration as the array-package. Fig. 1 shows the electroluminescence (EL) spectrum under 60 mA DC pump current for a single 200 × 200 μm flip-chip LED.