Uncooled Low-Bias Uni-Traveling Carrier Photodetectors
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Abstract: We demonstrate state-of-the-art uncooled photodetectors for low-bias (2-4V) operation with high responsivities, high saturation currents, and broad bandwidths. High responsivity (1.09A/W), high bandwidth (39GHz) and the OIP3 (47dBm) were achieved at -3V bias.

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Photodiodes with high speed, high responsivity, and high linearity are key components for photonic links. As uni-traveling carrier photodetectors (UTC-PDs) utilize only fast-traveling electrons as active carriers, they show excellent high speed and high power performance compared to p-i-n photodetectors. Recently most work has been focused on increasing the detector bandwidth, responsivity and third-order output intercept point (OIP3) [1-4], yet what is of the same importance is reducing the bias voltage, which simplifies the electronic design and reduces power consumption. In this work, we describe novel designs using an electric field (E field) dependent electron drift velocity model for achieving low bias operation. These UTC-PDs can operate with low reverse bias of 2V, which is much lower than references [1-4]. As a result, our UTC-PDs can work with high photocurrent (75mA, -3V bias) at room temperature without any external cooling system. Ultra high responsivity of 1.09A/W was obtained for a 10µm x 120µm [Ridge width x Length] detector at 1550nm optical wavelength. The highest bandwidth of 39GHz was achieved for a 6µm x 20µm back facet high-reflection (HR) coated UTC-PD. The highest OIP3 of 47dBm was obtained for a straight waveguide 10µm x 100µm UTC-PD at 315MHz frequency. The saturation currents are higher than 60mA (limited by experiment setup).

An array of geometries of the waveguide-coupled UTC-PDs were designed and fabricated. The widths vary from 6µm to 12µm, and the lengths from 20µm to 135µm to achieve different bandwidth-responsivity combinations. The UTC-PD structure was designed for a 58.2GHz transit-time bandwidth and grown on semi-insulating InP substrates by metal-organic vapor deposition (MOCVD). The epitaxial structure consists of a diluted waveguide region, a low doped collector region, an InGaAs absorber region and an InP cladding region. We designed two new geometries besides the straight waveguide UTC-PDs, (1) tapered UTC-PDs and (2) back facet HR coated UTC-PDs (reflectivity >0.98). The tapered design has the advantages of similar detector length but ~ 30% smaller detector area (~30% smaller junction capacitance) in comparison with the straight waveguide detectors. The HR coated detector reflects the light back to the detector active region, thus increasing the effective length by a factor of 2.

Two methods were applied to achieve low bias operation, (1) introducing bandgap smoothing layers between absorber and collector layer and (2) optimizing electron drift velocity in the collector region using the E field dependent drift velocity model. First, graded layers were used to smooth out the bandgap discontinuity between the InGaAs absorber and the InGaAsP collector. This reduces the E field drop, and facilitates low bias operation. Second, the E field across the low doped collector region was optimized to match the drift velocity overshoot effect [5]. The E field was simulated using the device simulator from Silvaco, Co. Ltd.. With constant bias of -3V, the E field distribution is determined by the collector thickness. Therefore, the average electron drift velocity is a function of collector thickness as shown in Fig. 1 (a). For -3V bias, a collector thickness of 525nm creates an optimum E

Fig.1 (a) Simulated average electron drift velocity as a function of collector thickness at -3V bias. (b) The normalized RF output power as a function of detector bias voltage for a 12 µm x 120 µm detector

Fig.2 Simulated responsivity for a straight waveguide UTC-PD with perfect coupling condition and measured responsivities for straight waveguide (regular), tapered and HR coated UTC-PDs
field, which peaks the electron average drift velocity at 1.02E7 cm/s. The design was verified by measuring normalized RF output power with different bias voltage, and results are shown in Fig. 1 (b). From Fig. 1 (b), the output RF signals peaked at -3V bias as designed. The results also indicate that our detector can operate in a range from -2V to -4V bias without dropping 1dB of peak RF power at very high photocurrent of 75mA, allowing for robust voltage handling in a noisy electrical environment. The experimental and simulation results also indicate that the RF power roll-off is much faster at low bias region than the high bias region.

Small core fibers with 5µm core diameters were used to couple light into the detectors. Fig. 2 shows simulated and measured responsivities for different geometries at optical wavelength of 1550nm. Detectors with narrower ridge widths show lower responsivities comparing with detectors with wider ridge widths due to the higher coupling losses. HR coated detectors have (10% to 25%) higher responsivity compared with straight waveguide UTC-PDs of the same length. Tapered UTC-PDs have similar responsivities as straight waveguide ones with the same length. The highest responsivity of 1.09A/W was obtained for a 10µm x 120µm detector.

Bandwidths were measured using a 40GHz modulator and a HP 8722C network analyzer. Fig.3 (a) shows simulation results and experimental data for bandwidth-versus-detector-area measurements. The measured electro-optic bandwidths follow the same trend of the simulation results, except that it is lower due to the parasitic capacitance (~10fF) generated by the contact metal pads and a spurious length-dependent capacitance due to fabrication. A 6µm x 20µm HR coated detector showed a 3dB bandwidth of 39GHz. Large-area (>1000 µm²) devices were designed for high efficiency (>1A/W) and power handling (>50mA photocurrent). Fig. 3 (b) shows the eletro-optic 3dB bandwidth as a function of bias for an 8µm x 120µm UTC-PD. The detector bandwidth stays constant (~20GHz) at 32mA photocurrent when reverse bias is larger than 2V.

The OIP3s were measured using standard two-tone method. Fig.4 (a) shows the OIP3 of a 10µm x 100µm UTC-PD at 315MHz. From Fig. 4 (a), OIP3 are higher than 43dBm, when reverse bias is higher than 2V. The highest OIP3 (47dBm) was obtained at -3V bias. OIP3 at different frequencies were also measured, and an OIP3 of 36dBm at 10GHz and 33dBm at 20GHz were observed. The saturation current (or 1dB compression current) measurement is shown in Fig. 4 (b). No compression was observed up to ~18dBm (63mA) photocurrent (limited by EDFA power) up to 20GHz RF frequency, indicating that the compression current is significantly higher.

In conclusion, we describe a novel photodiode design to achieve low-bias operation at 1.55 µm wavelength. The electron drift velocity overshoot effect was observed. Under -3V reverse bias, state-of-the-art performance has been achieved. Ultra high responsivity (1.09A/W), broad bandwidth (39GHz), high OIP3 (47dBm) and high saturation current (>60mA) has been demonstrated. These devices have been used in demonstration of low noise figure, high dynamic range RF photonic links.

References