Design of a Uni-Traveling-Carrier (UTC) photodetector in InP Membrane on Silicon (IMOS)

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InP Membrane on Silicon (IMOS) technology provides a new platform for integrating a full set of photonic components on top of CMOS chips. In this paper, a design of a uni-traveling-carrier photodetector in this platform is presented. Optical simulations have been performed to determine both the coupling loss and the metal loss. Electrical simulations have also been performed to optimize the RC constant and the transit time. The simulation shows that a bandwidth beyond 100 GHz with a responsivity of 0.8 A/W can be achieved. This provides promising integrated solutions for ultrafast optical interconnects and microwave applications.

Introduction

InP Membrane on Silicon (IMOS) technology promises the integration of ultra-small active and passive photonic devices in a single layer. This photonic membrane layer is bonded on a silicon wafer with polymer benzocycolbutene (BCB). By combining the best features of InP related material and Si based chips, IMOS opens up a wide range of applications with potential improvements in speed, integration density and energy consumption. Recently, a variety of passive components have been realized in this platform [1] and an electrically pumped membrane laser at 1.55 µm is being developed [2]. In this paper, a design of a photodetector (PD) in the IMOS platform is reported.

The uni-traveling-carrier (UTC) structure is chosen due to its superiority in bandwidth and power handling capability. The carrier transport in UTC-PDs is dominated by electrons due to the utilization of a p-type doped absorption layer [3]. The higher velocity of electrons than that of holes results in a higher bandwidth compared to conventional PIN-PDs. Furthermore, the space charge effect is also reduced, leading to a higher saturation current. These features of UTC-PDs provide new integration solutions for applications in coherent photonics and microwave photonics [4].

Structure design

The structure of our UTC-PD is shown in Fig. 1. The width of the mesa is designed as 3 µm. A 300 nm thick undoped InP layer is used both as the passive waveguide and as the electron collector (depleted) in the UTC region. A 150 nm thick p-type (Zn) doped InGaAs layer is used both as the absorber and the p-contact. In this way the photodetector can achieve a high responsivity while maintaining a simple layer stack which is desired for active/passive integration in the membrane platform. The doping concentration in the InGaAs layer is graded from 10^{18} cm^{-3} at the collector-absorber interface to 10^{19} cm^{-3} at the contact surface. A quasi-field formed by this graded doping profile defines the diffusion direction of electrons (toward the collector) and reduces their transit time in this absorber [3]. Hence, the graded doping design is crucial for high collection efficiency and high bandwidth. To further enhance the performance a novel double-side processing technology will be developed: p-metals (Ti/Pt/Au) are firstly evaporated on one side; after bonding this InP sample onto a silicon substrate, the remaining processing steps are performed from the other side.

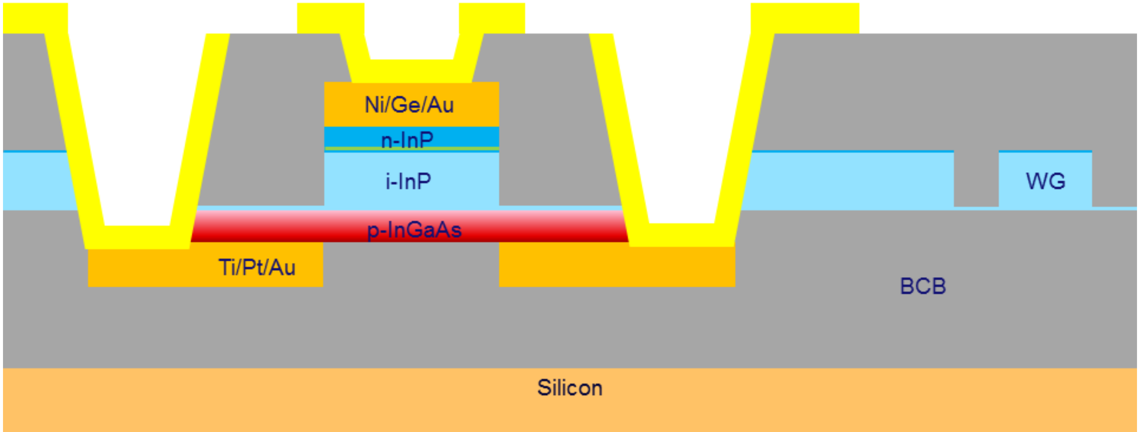

Fig. 1. Cross-section of the UTC-PD (not to scale)

Responsivity

In order to determine the responsivity of the UTC-PD, optical simulations are performed by using a fully vectorial mode solver and a 3D optical propagation tool based on eigenmode expansion (Fig. 2) [5]. The modal absorption coefficient is calculated to be 3600 cm^{-1} at 1.55 µm, which implies that over 97% of the input light will be absorbed within a length of 10 µm. The metal loss is estimated by setting the absorption coefficient of InGaAs to be zero and only taking into account the absorption in the metal contacts. This approximation gives a number of 340 cm^{-1}, indicating that the loss due to the metal contacts is limited. The coupling of the input signal from the waveguide to the photodetector region is also simulated. The coupling coefficient from the fundamental mode in the waveguide to the one in the photodetector is 75% from this simulation; the rest are coupled to higher order modes which suffer more from the metal loss. Other factors that may influence the efficiency are also taken into account. The free carrier absorption is negligible compared to the material absorption of InGaAs. The minority diffusion length in the Zn doped InGaAs with a doping concentration between 10^{18} cm^{-3} to 10^{19} cm^{-3} is one order of magnitude larger than the InGaAs layer thickness [6], implying that the collection efficiency will not be affected by the doping level. Overall, the coupling is the limiting factor of the device efficiency and a responsivity of 0.8 A/W is predicted for a 10 µm long photodetector.

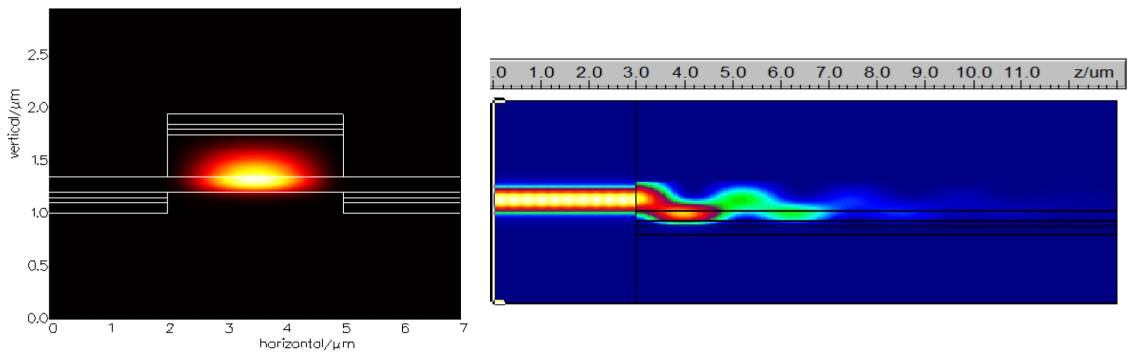

Fig. 2. Optical simulation results showing the fundamental mode profile (left) and the coupling from the waveguide to the photodetector (right)

Bandwidth

The bandwidth of a photodetector is limited by the RC time constant and the carrier transit time. The junction capacitance of a UTC-PD with 10 µm length, 3 µm width and a 0.3 µm thick depletion layer is as low as 10 fF. The parasitic capacitance can be neglected by planarizing thick BCB as isolation from the silicon substrate. The relatively high sheet resistance of a thin membrane device is the major limiting factor for the bandwidth. In this structure, however, the series resistance can be reduced dramatically by putting the p-metals close to the mesa, which is the major advantage of the double-side processing technology. The contact resistance on both p and n sides are currently being optimized to the target value of 3×10^{-6} Ωcm^2. A stationary electrical simulation is performed with COMSOL to determine the total resistance (Fig. 3). It is assumed that the illumination results in a uniform carrier distribution in the depletion region. A resistance below 50 Ω is obtained from the simulation with the dimensions and the contact resistivity mentioned above. By using the equation

$$f_{3db,RC} = \frac{1}{2\pi \cdot R \cdot C}$$

The bandwidth limited by the RC constant is calculated to be as high as 150 GHz in a 50 Ω load environment.

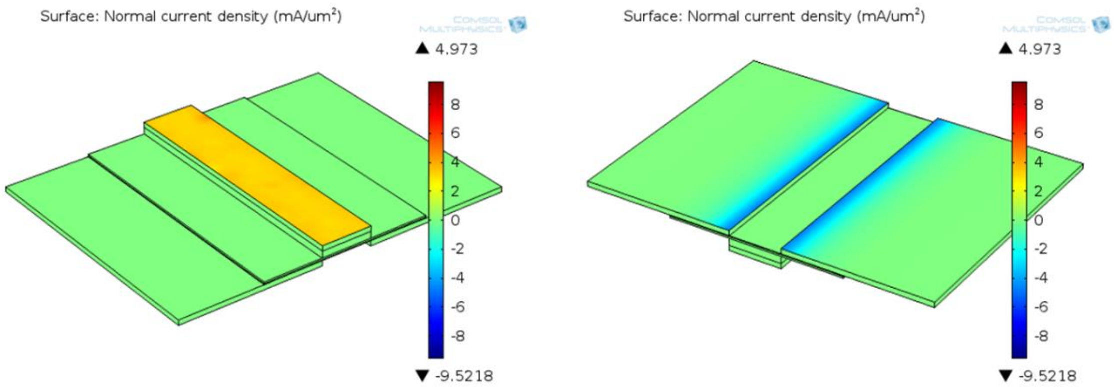

Fig. 3. Electrical simulation results showing the surface normal current density at -5 V bias

The transit time of UTC-PDs consists of two terms: the electron diffusion time in the undepleted InGaAs absorber, and the electron drift time in the depleted InP collector. The first term is studied in detail in [3] by considering the electron diffusion transport, thermionic emission process and the effect of the quasi-field. Based on this study, the diffusion time is estimated to be below 1 ps for a 150 nm thick InGaAs absorber with a graded doping from 10^{18} cm^{-3} to 10^{19} cm^{-3}. In terms of the electron drift time, UTC-PDs are usually set with an optimal bias voltage so that electrons travel at the velocity overshoot (above 2×10^7 cm/s, 5 times higher than the velocity of holes). At this optimal bias, the electron drift time through the 300 nm collector is only 1.5 ps. The bandwidth limited by a total transit time of 2.5 ps is calculated to be 150 GHz by the following equation:

$$f_{3db,tr} = \frac{2.4}{2\pi \cdot \tau_{tr}}$$

Taking into account the RC constant limited bandwidth of 150 GHz, the final bandwidth of such a UTC-PD is expected to be beyond 100 GHz according to the equation:

$$\frac{1}{f_{3db,total}^2} = \frac{1}{f_{3db,RC}^2} + \frac{1}{f_{3db,tr}^2}$$

Other considerations

The power handling capability of a photodetector is very important particularly in coherent photonics and microwave applications. The saturation output of a photodetector is mainly limited by space charge effects and thermal failure. UTC-PDs show much reduced space charge effects due to the high electron velocity in the depletion layer. In terms of thermal effects, it becomes more severe in a membrane device with materials of low thermal conductivity (SiO_2 and BCB) blocking the heat dissipation to the substrate. In this design with double-side processing, the metals on both sides of the UTC-PD are expected to help to dissipate the heat to large-area metal pads on top. Followed by top cooling approaches, the thermal management of this design can be very effective.

The IMOS platform aims at providing a technology for photonic integrated circuits (PICs). By developing the double-side processing technology, we expect to integrate this UTC-PD with other components like lasers, by just adding layer stacks and a few processing steps from one of the two sides. In addition, the relatively simple layer stack allows selective-area regrowth as an alternative approach for the integration.

Conclusions

A high performance UTC photodetector in InP membrane on Silicon is designed. A bandwidth beyond 100 GHz and a responsivity of 0.8 A/W are shown by simulations. Moreover, it has the potential for fully integrated, high power applications.

References

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