Modeling and Measurement of a HSQ Passivated UTC-PD with a 68.9 GHz Bandwidth

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***Abstract*—An InGaAs uni-traveling-carrier photodiode passivated using hydrogen silsesquioxane (HSQ) is reported. The device was fabricated and also simulated using 3D full-wave and equivalent circuit modeling. Both experimental and modeled results show a –3 dB frequency bandwidth of 68.9 GHz at –3 V bias.**

Keywords—*Photodetector, Uni-traveling carrier (UTC), 3D full-wave simulation, Equivalent circuit, Hydrogen silsesquioxane (HSQ)*

I. INTRODUCTION

Photodiodes (PDs) are effective photomixer devices for continuous-wave (CW) Terahertz (THz) sources [1]. A preferred design is the uni-travelling-carrier photodiode (UTC-PD) which has a large bandwidth and low operation voltage compared with conventional PDs [2]. Although a UTC-PD with a maximum bandwidth as high as 310 GHz (at –0.5 V) was reported as long ago as 2000, the device used a thin absorption layer of 30 nm and small junction area of 5 μm^2, which resulted in a low responsibility of 0.07 A/W [3]. Recently, a UTC-PD passivated with SU-8 has been reported, with dimensions of 5 μm × 7 μm, a –3 dB bandwidth of 85 GHz and responsivity of 0.26 A/W [4]. A UTC-PD with graded doping in the absorption layer and larger dimensions of 4 μm × 15 μm was reported with a predicted responsivity as high as 0.81 A/W and a maximum bandwidth around 35 GHz (at –1 V) [5], the bandwidth being limited by the parasitic capacitance between the n- and p-contact mesas. Here, we report a similar UTC-PD structure with even larger dimensions of 4 × 20 μm, in which the sidewalls are passivated with hydrogen silsesquioxane (HSQ). The HSQ layer reduces the parasitic capacitance to 1 fF, as well as serving as an insulation pad and supporting structure to interconnect with the RF signal pad. HSQ is a spin-on dielectric material, chemically similar to SiO_2, that can be used to passivate and planarize structured surfaces. The frequency responses of the S_{11} scattering parameter and impedance were simulated using the 3D full-wave model in the CST STUDIO SUITE and using an optimized equivalent circuit [6]. Both the modelled and measured results indicate a bandwidth of 68.9 GHz at –3V bias voltage, much higher than that of 35 GHz reported in [5].

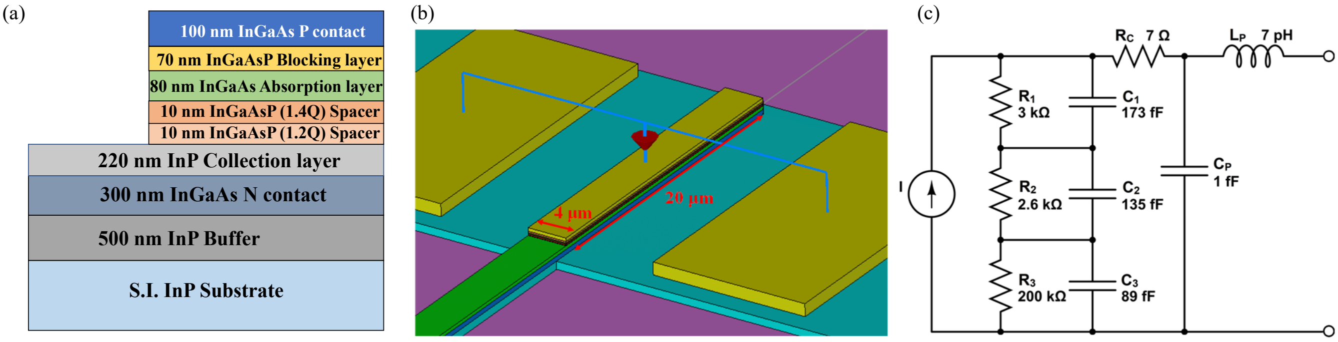

Fig. 1. (a) Epitaxial layer structure of UTC-PD, (b) CST 3D full-wave modeling layout, (c) equivalent circuit model at a bias voltage of -3 V.

II. DEVICE FABRICATION AND MODELING

The epitaxial layer structure of the device is illustrated in Fig. 1(a). The wafer was grown by metal–organic vapor phase epitaxy (MOVPE) on a semi-insulating InP substrate. The PD absorption waveguide and the passive waveguide were created separately by dry etching using a $CH_4/H_2/O_2$ gas mixture, and then the same dry etch process was used to remove the InP buffer to give electrical

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isolation between devices. HSQ was spun on for ridge waveguide planarization and baked in an oven at 180 ℃. A Ti/Pt/Au multilayer structure was used for both the n-contact and p-contacts, with using lift-off to define the ground-signal-ground high frequency probing pads. The 3D layout was established in CST STUDIO SUITE as shown in Fig. 1(b). In the full-wave impedance model, two n-contact mesas were connected by a perfect electric conductor (PEC) wire. A discrete port connected this wire to the p-contact mesa. For full-wave frequency modelling, the excitation source was replaced with a 50 Ω load, representing the input impedance of the network analyzer used in the measurement. An ideal current source connected the n-contact layer to the absorption layer to simulate the photocurrent when the UTC-PD was illuminated. The equivalent circuit summarizing the optimized parameters is shown in Fig. 1(c). R_3 and C_3 represent the collection layer. The two spacer layers are represented by the R_2 and C_2, and R_1 and C_1 parallel circuits, respectively. R_C is the resistance of the heavily doped contact layers and ohmic contacts. The parasitic capacitance and inductance between the n- and p-contact mesas are C_P and L_P respectively. The current source 'I' accounts for the photocurrent.

III. Device Simulation and Measurement

The magnitude and phase of the S_{11} parameter and impedance of our device at –3 V bias calculated using the 3D full-wave and equivalent circuit models are illustrated in Fig. 2(a) – (d), and compared with measurements up to 60 GHz. Figure 3(e) illustrates the band diagram of our structure at zero bias, calculated using a Discontinuous Galerkin Time-Domain (DGTD) solver. The measured and simulated frequency responses at –3 V bias are presented in Fig. 3(f), and show a 68.9 GHz bandwidth. There is close agreement between the modelled and measured results. Figure 3(g) shows cross-section SEM picture of the PD with planarization HSQ.

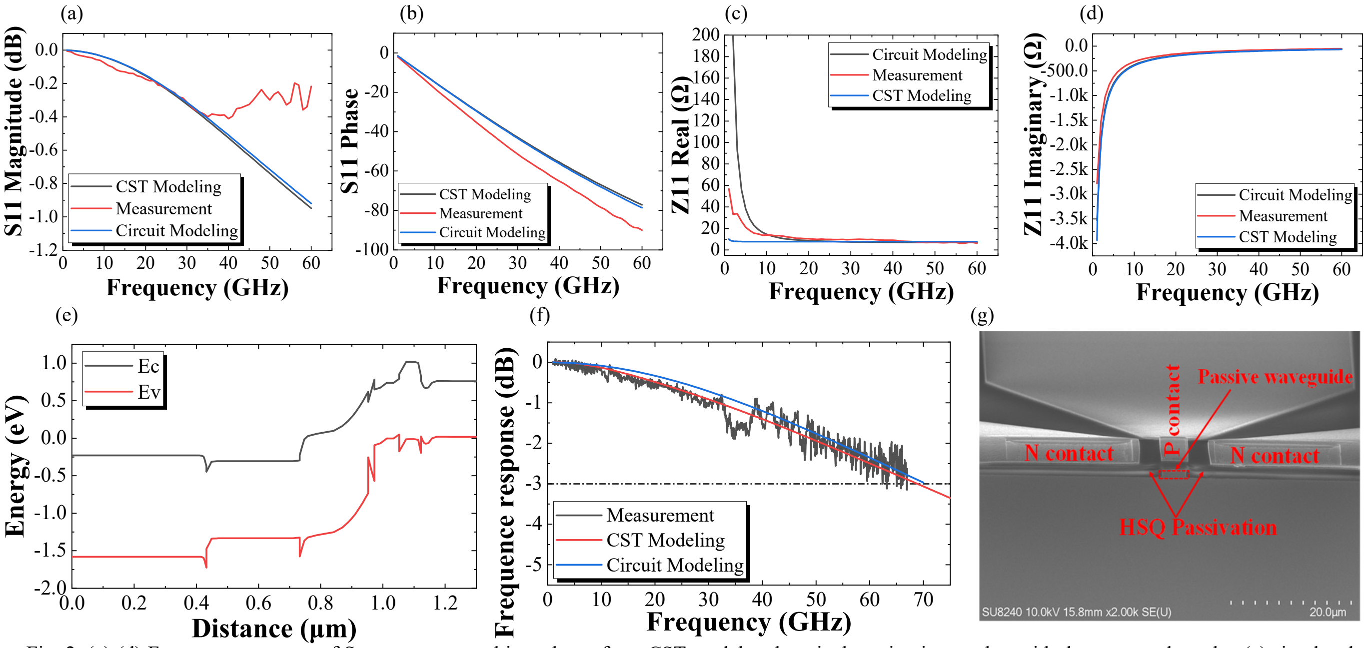

Fig. 2. (a)-(d) Frequency response of S_{11} parameters and impedance from CST model and equivalent circuit, together with the measured results, (e) simulated band diagram at 0 V from DGTD solver. (f) Comparison of frequency response in CST, equivalent circuit, and measurement at −3 V bias. (g) SEM picture of the cross-section of the device with HSQ planarization.

IV. Conclusion

In summary, a HSQ Passivated UTC-PD was modelled, fabricated and measured. The frequency response of the impedance and S_{11} scattering parameter were simulated by 3D full-wave modelling and equivalent circuit analysis. Both the experimental and simulated data show that a 4 × 20 µm UTC-PD can achieve a 68.9 GHz bandwidth at –3 V bias, opening many opportunities for future compact mm-wave and THz systems.

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