# 45 GHz bandwidth-efficiency resonant cavity enhanced ITO-Schottky Photodiodes

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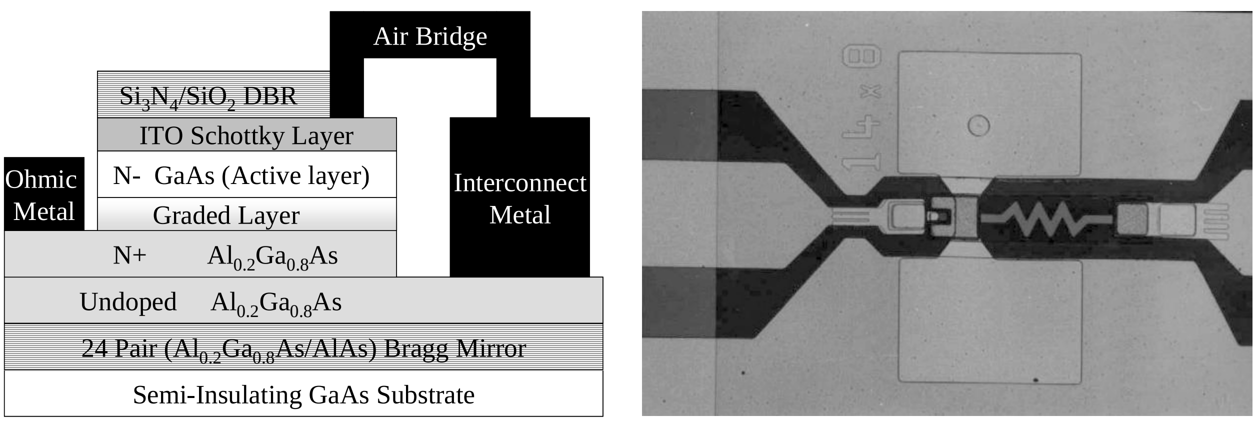
**Abstract:** We demonstrated high-performance resonant cavity enhanced ITO-Schottky photodiodes. We achieved a peak efficiency of 75% around 820 nm with a 3-dB bandwidth of 60 GHz resulting in a bandwidth-efficiency product of 45 GHz.

**OCIS codes:** (040.5160) Photodetectors, (320.7080) Ultrafast devices

High-performance optical communication and measurement systems require photodetectors with high bandwidth-efficiency (BWE) products [1]. The BWE product of conventional photodiodes (PD) is limited due to the bandwidth-efficiency trade-off. Resonant cavity enhanced (RCE) photodetection scheme offers the possibility to overcome this limitation [2]. High BWE products were already achieved using Schottky, p-i-n and avalanche type of RCE-PDs, which could not be reached with conventional detector structures [3-8]. Theoretical simulations predict even better performances for RCE Schottky photodiodes if the optical losses and scattering caused by the Schottky metal - which also serves as the top mirror of the resonant cavity – could be avoided. Indium-tin-oxide (ITO) which is known to be a transparent conductor is a potential alternative to thin semi-transparent Au as the Schottky-contact material [9,10]. Recently we have demonstrated RCE ITO-Schottky PDs with 20 GHz BWE at 840 nm [11]. In this paper, we report our work on high-performance AlAs/GaAs-based RCE ITO-Schottky PDs operating around 820 nm with 45 GHz BWE product.




**(a)** **(b)**

Fig. 1. (a) Cross section of a fabricated RCE ITO-Schottky PD. (b) Photograph of a high-speed RCE ITO-Schottky PD.

Figure 1(a) shows the epitaxial layer structure of a fabricated RCE ITO-Schottky PD with a dielectric top Bragg mirror. The resonant cavity was formed by a MBE-grown $Al_{0.2}Ga_{0.8}As$/AlAs distributed Bragg reflector (DBR) bottom mirror and a PECVD-grown $Si_3N_4/SiO_2$ DBR top mirror, both centered at 820 nm. The samples were fabricated by a 8-step microwave-compatible fabrication process. Fabrication started with the formation of ohmic contacts to n+ layers. Mesa isolation was followed by a Ti-Au interconnect metalization. Then, we deposited a 100 nm thick ITO film that acted as the Schottky layer, and a 150 nm thick $Si_3N_4$ passivation layer. Finally, to reduce the parasitic capacitance and improve the high-frequency characteristics of the detector, a thick Ti-Au layer was evaporated to form an air-bridge connection between the interconnect metal and the ITO Schottky layer. Figure 1(b) shows a microphotograph of a completed small-area, high-speed RCE ITO-Schottky PD. The resulting RCE Schottky PDs had breakdown voltages around 6-7 V and typical dark current values of 0.1 nA at –1 V bias for a $5x5\mu m^2$ device.

The ITO deposition was achieved by RF magnetron sputtering in an Ar environment from a composite target containing by weight 90% $In_2O_3$ and 10% $SnO_2$. We have measured the thin-film characteristics of ITO before the device fabrication. The resistivity of our ITO films were measured to be around $2x10^{-4}\Omega$-cm. This value decreased to $1.5x10^{-4}$ and $1.2x10^{-4}$ $\Omega$-cm when the films were annealed at 300 $^oC$ and 400 $^oC$, respectively. Using a fiber optic based optical transmission measurement set up, we measured the transmittivity of a 150 nm-thick ITO film. The transmittivity was around 87% at 820 nm, and did not change significantly with annealing. Reflectivity at the same wavelength was measured as ~12% which indicated that the absorption in ITO was almost negligible. Ellipsometry measurements showed that the as-grown ITO film had a refractive index of 1.99. This value decreased to 1.85 for an annealing temperature of 450 $^oC$. These results clearly convinced us that the sputtered ITO films should be able to make low-loss, high-quality Schottky contacts to our devices.

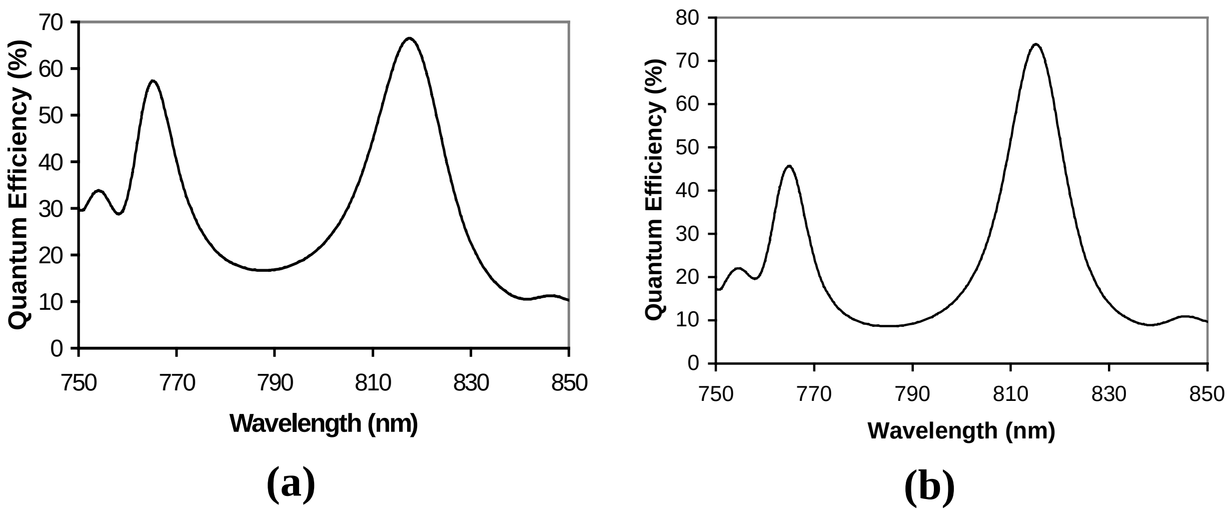



Fig. 2. Spectral quantum efficiency of the RCE ITO-Schottky PD (a) without top DBR, (b) with 2 pair top DBR

Photoresponse of the fabricated devices were measured in the 750-850 nm spectral range by using a set-up consisting of a tungsten-halogen projection lamp as the source, single-pass monochromator, multi-mode fiber, lightwave probe, probe station and a lock-in amplifier. Figure 2(a) shows the spectral quantum efficiency measurement under zero bias of the RCE-PD without top Bragg mirror. The measured spectral photoresponse of the same device with 2 pair $Si_3N_4/SiO_2$ top DBR is shown in Figure 2(b). The deposition of top DBR has increased the peak efficiency from 66% to 75% at 815 nm.

High-speed measurements were implemented by utilizing a picosecond (full-width-at-half-maximum (FWHM) is 1.3 psec) mode-locked Ti-sapphire laser tuned at the resonant wavelength of our detectors. The devices were illuminated using a single-mode fiber on a microwave probe station and the resulting pulses were observed on a 50 GHz sampling scope. The pulse response of the detector was observed to be bias-dependent. While 12 psec FWHM was measured at zero bias, this value decreased to 11.5 psec for 2 V reverse bias voltage. The best measured FWHM was 11.2 psec under a reverse bias of 4 V. Further increasing of the bias voltage made the PD response slower, mainly due to the avalanche gain mechanism which was significant for bias values higher than 5 V. Figure 3(a) shows the measured temporal response of a small area ($5x5\mu m^2$) RCE ITO-Schottky PD under 4 V reverse bias. The Fourier transform of the temporal data has a 3-dB bandwidth of 43 GHz. The measured data was corrected by deconvolving the scope response. Considering a 9 psec FWHM for the 50 GHz scope, our detectors had a 3-dB bandwidth of 60 GHz. Figure 3(b) shows the as-measured and corrected frequency responses obtained by taking the fast Fourier transform (FFT) of the temporal detector response. The efficiency and bandwidth measurements of the fabricated RCE ITO-Schottky PDs result in a detector performance of 45 GHz BWE product.

In summary, we have demonstrated high-speed, high-efficiency RCE Schottky PDs using transparent ITO Schottky contact material and dielectric top Bragg mirror. The peak efficiency and 3-dB bandwidth values obtained from these detectors combine for a BWE product of 0.75x60 GHz = 45 GHz. To the best of our knowledge, this is the highest detector performance reported to date for vertically illuminated Schottky PDs.

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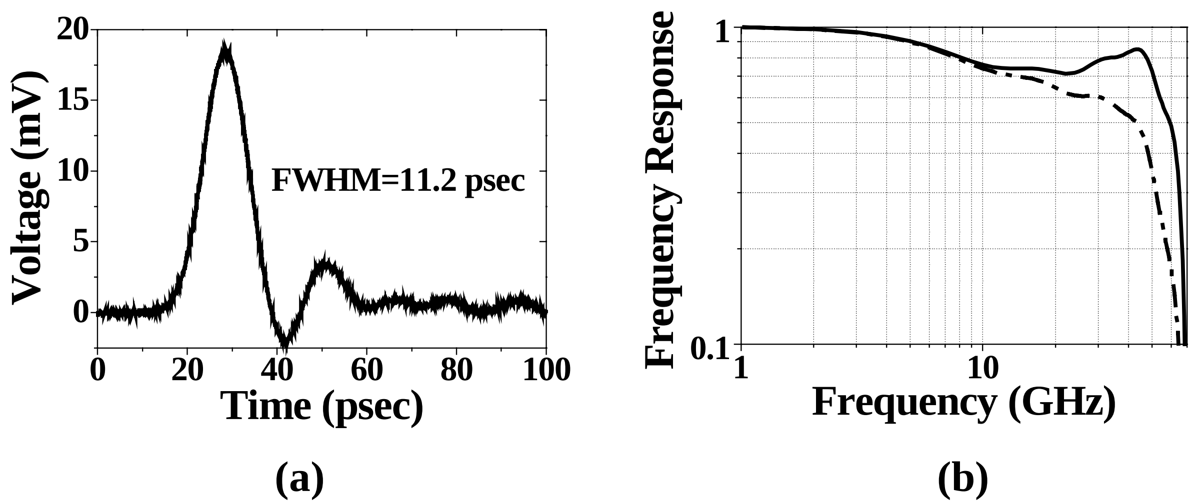


Fig. 3. (a)Pulse response of a 5x5 $\mu m^2$ ITO-RCE Schottky photodiode. (b)FFT of the detector, as-measured (dashed line) and corrected by assuming a Gaussian pulse for the scope response (solid line).


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