45-GHz Bandwidth-Efficiency Resonant-Cavity-Enhanced ITO-Schottky Photodiodes

Necmi Biyikli, *Student Member, IEEE*, Ibrahim Kimukin, *Student Member, IEEE*, Orhan Aytür, *Member, IEEE*, Mutlu Gökkavas, M. Selim Ünlü, *Senior Member, IEEE*, and Ekmel Ozbay, *Member, IEEE*

***Abstract*—High-speed Schottky photodiodes suffer from low efficiency mainly due to the thin absorption layers and the semitransparent Schottky-contact metals. We have designed, fabricated and characterized high-speed and high-efficiency AlGaAs–GaAs-based Schottky photodiodes using transparent indium–tin–oxide Schottky contact material and resonant cavity enhanced detector structure. The measured devices displayed resonance peaks around 820 nm with 75% maximum peak efficiency and an experimental setup limited temporal response of 11 ps pulsewidth. The resulting 45-GHz bandwidth-efficiency product obtained from these devices corresponds to the best performance reported to date for vertically illuminated Schottky photodiodes.**

***Index Terms*—Bandwidth-efficiency, high-speed, indium–tin–oxide, photodides, photodetectors, resonant-cavity enhancement, Schottky photodiode.**

I. Introduction

HIGH-PERFORMANCE photodiodes (PDs) are essential optoelectronic components for applications where ultrafast photodetection is needed, i.e., optical communication, measurement, and sampling systems [1]. The PD performance is measured by the bandwidth-efficiency product (BWE) and is limited for conventional vertically illuminated photodiodes (VPDs) due to the bandwidth-efficiency tradeoff [2]–[5]. This tradeoff arises from the fact that the quantum efficiency and bandwidth of a conventional VPD, have inverse dependencies on the photoabsorption layer thickness. To overcome the BWE limitation for such conventional VPDs, two alternative detection schemes were offered: edge-coupled photodiodes and resonant-cavity-enhanced photodiodes (RCE-PDs). Both PD structures have demonstrated excellent performances and are potential candidates as photodetectors for future high bitrate optical communication systems [2]. The ease of fabrication, integration, and optical coupling makes the RCE-PD more attractive for high-performance photodetection.

RCE-PD structure is formed by placing the conventional VPD inside a Fabry–Perot resonant microcavity. Only the incident photons, which are at the resonance wavelength of the detector cavity are recycled between the mirrors of the cavity, so that the quantum efficiency is dramatically enhanced at this wavelength. Therefore, by using RCE-PD with a thin active layer, high- efficiency values can be achieved without lowering the detector bandwidth [5]. Extremely high BWE values are achieved using Schottky, p-type-intrinsic-n-type (p-i-n), and an avalanche type of RCE-PDs, which could not be reached with conventional VPD structures. 100-GHz bandwidth [6] and 25-GHz BWE [7] for Schottky, 46-GHz BWE [8] for p-i-n, 35-GHz low-gain bandwidth, [9] and 17-GHz BWE [10] for avalanche type of RCE-PDs are the record performances reported to date.

Theoretical simulations predict even better performances for RCE Schottky PDs if one can get rid of the optical losses and scattering caused by the Schottky metal, Au, which also serves as the top mirror of the RC [7], [11]. Indium–tin–oxide (ITO), which is known to be a transparent conductor, is a potential alternative to thin semitransparent Au as the Schottky-contact material. Its transparency minimizes the problem of optical loss and scattering, resulting in higher efficiency performance [12], [13]. Recently, we have demonstrated an RCE ITO-Schottky PD with $\sim$ 20-GHz BWE at 840 nm, using a dielectric top mirror [14]. In this letter, we present our work on design, fabrication, and characterization of high-speed 45-GHz BWE AlAs-GaAs based RCE ITO-Schottky PDs operating around 820 nm.

TABLE I
Epitaxial Layer Design of the RCE Schottky Photodiode

Material	Thickness	Doping
GaAs	150 nm	Undoped
GaAs → $Al_{0.2}Ga_{0.8}As$	30 nm	Undoped
$Al_{0.2}Ga_{0.8}As$	400 nm	N+ $2x10^{18}cm^{-3}$
$Al_{0.2}Ga_{0.8}As$	180 nm	Undoped
$Al_{0.2}Ga_{0.8}As$/AlAs DBR	24x(59nm/68nm)	Undoped
Semi-Insulating GaAs Substrate		

II. Design and Fabrication

The epitaxial structure of the RCE Schottky PD was designed using the transfer-matrix-method (TMM) based theoretical simulations (Table I). The layers were grown by molecular beam epitaxy on a semi-insulating GaAs substrate. In order to achieve a low-loss RC around the design wavelength, a highly reflecting bottom mirror was formed using a 24-pair

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N. Biyikli and O. Aytür are with the Department of Electrical Engineering, Bilkent University, Bilkent Ankara 06533, Turkey (e-mail: biyikli@fen.Bilkent.EDU.TR).

I. Kimukin and E. Ozbay are with the Department of Physics, Bilkent University, Bilkent Ankara 06533, Turkey.

M. Gökkavas and M. S. Ünlü are with the Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215 USA.

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$Al_{0.2}Ga_{0.8}As - AlAs$ distributed Bragg reflector (DBR) centered at 820 nm. All the cavity layers except the 150-nm-thick GaAs absorption layer were transparent at the operation wavelength. No diffusion component of the photocurrent was expected in this heterostructure RCE-PD design, since no absorption occured in any other cavity layer.

The deposition of the Schottky-contact material ITO was done via RF magnetron sputtering in an Ar environment from a composite target containing by weight 90% In_2O_3 and 10% SnO_2. Before device fabrication, electrical, and optical properties of sputtered thin ITO films were characterized. The resistivity of the as-grown ITO film was determined approximately 2×10^{-4} Ω·cm. This value decreased to 1.5×10^{-4} Ω·cm and 1.2×10^{-4} Ω·cm when the films were annealed at 300 °C and 400 °C, respectively. Using a fiber-optic based optical transmission measurement setup, the transmittivity of a 150-nm-thick ITO film deposited on a quartz substrate was measured. The transmittivity was around 87% at 820 nm, and increased very slightly (to $\sim 88\%$) with annealing up to 450 °C. Reflectivity at the same wavelength was measured to be 12% before annealing, which indicated that the absorption in ITO film was $\sim 1\%$. Another important optical property was the refractive index of the film, which was measured by an ellipsometer. The measured refractive index of the as-grown ITO film was 1.99, and this value decreased to 1.85 after the film was annealed at 450 °C. These results showed that the sputtered ITO films could be used as low-loss high-quality Schottky contacts to our devices.

The samples were fabricated by an eight-step microwave-compatible fabrication process in a class-100 clean room environment. Fabrication started with the formation of ohmic contacts to the N^+ doped $Al_{0.2}Ga_{0.8}As$ layer using a self-aligned Au–Ge–Ni liftoff process. The samples were then annealed at 450 °C for 45 s. After mesa formation via wet-etch, Ti–Au interconnect metal was evaporated, which formed coplanar waveguide (CPW) transmission lines on top of the semi-insulating substrate. Afterwards, the Schottky-contact material, a 100-nm-thick ITO film was sputtered and patterned. The ITO film was etched to define the contact region using (1:40) HF:H_2O etchant. The next step was the growth of a ~150-nm-thick Si_3N_4 passivation layer. Besides passivation and protection of the ITO-Schottky surface, Si_3N_4 was also used as the dielectric of the metal–insulator–metal bias capacitors. To reduce the parasitic capacitance, the ITO-Schottky film was connected to the CPW pads by a 0.8-μm-thick Ti–Au airbridge. Finally, the top mirror of the RC was formed by a plasma-enhanced chemical vapor deposition-grown (PECVD) dielectric Si_3N_4–SiO_2 DBR centered at 820 nm. The resulting RCE-Schottky PDs had breakdown voltages around 8 V and typical dark current densities were 5×10^{-5} A/cm^2 at -1-V bias. By current–voltage measurements, the Schottky barrier height and the ideality factor of the ITO/GaAs Schottky contacts were determined as 0.74 eV and 1.12, respectively. Fig. 1 shows the picture of a fabricated small-area high-speed RCE ITO-Schottky PD.

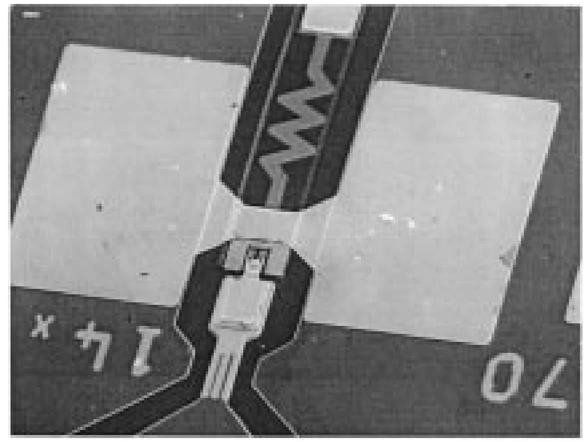
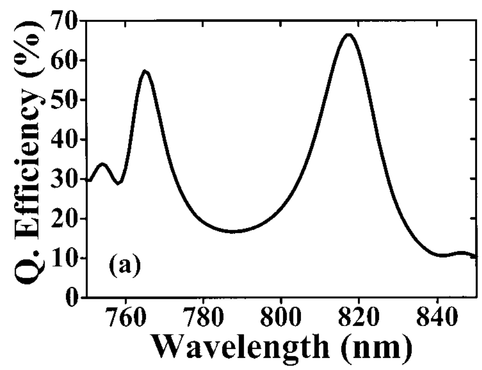
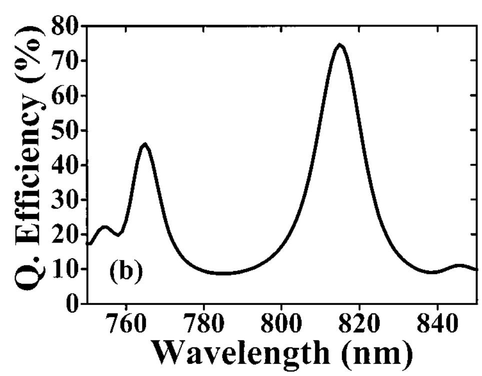


Fig. 1. Scanning electron microscope picture of a fabricated high-speed RCE ITO-Schottky photodiode.



(a)



(b)

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

III. Experimental Results

Photoresponse of the fabricated devices were measured in the 750–850-nm range. The experimental setup consisted of a tungsten–halogen projection lamp as the light source, single-pass monochromator, multimode fiber, lightwave probe, probe station, and a lockin amplifier. Fig. 2(a) shows the spectral quantum efficiency measurement of the RCE-Schottky PD without a dielectric top DBR mirror. The spectral quantum efficiency of the same device with a two-pair Si_3N_4–SiO_2 top Bragg mirror is shown in Fig. 2(b). The peak quantum efficiency before top DBR deposition was 66% at 817 nm and increased to a maximum of 75% at 815 nm for a two–pair top DBR mirror. Both measurements were done at zero bias. The peak quantum efficiency did not change with applied

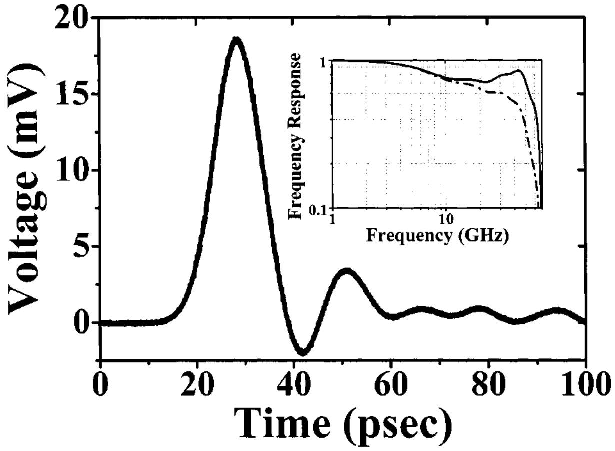


Fig. 3. Pulse response of a 5×5 μm^2 RCE ITO-Schottky PD. The inset shows the as-measured (dashed line) and deconvolved (solid line) frequency responses of the detectors.

bias voltage, which indicated that the diode active layer was completely depleted.

High-speed measurements were implemented by utilizing a picosecond mode-locked Ti:sapphire laser, which was tuned at the resonant wavelength of our detectors at 815 nm. The devices were illuminated by 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-ps full-width at half-maximum (FWHM) was measured at zero bias, this value decreased to 11.5 ps for 2-V reverse bias voltage. The best measured data had a FWHM of 11.2 ps under a reverse bias of 4-V. Further increase of the bias voltage made the PD response slower, mainly due to the avalanche gain mechanism, which was significant for bias voltages higher than 5 V. Fig. 3 shows the measured temporal response of a small area $(5 \times 5\ \mu\text{m}^2)$ 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-ps FWHM for the 50-GHz scope, our detectors had a 3-dB bandwidth of 60-GHz. The inset figure in Fig. 3 shows the as-measured and deconvolved frequency responses obtained from the fast Fourier transform of the temporal detector response. The efficiency and bandwidth measurements of the fabricated RCE ITO-Schottky PDs resulted in a detector performance of 45-GHz BWE product.

IV. Conclusion

We have demonstrated high-speed high-efficiency RCE Schottky PDs using transparent ITO Schottky contact material and a dielectric top Bragg mirror. After deconvolution of the scope response, the 3-dB bandwidth of the PDs was 60-GHz. Along with a 75% peak quantum efficiency, the BWE product obtained from these detectors was 45-GHz. To the best of our knowledge, this is the highest BWE product reported for vertically illuminated Schottky PDs.

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