Fabrication of High-Speed Resonant Cavity Enhanced Schottky Photodiodes

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***Abstract*— We report the fabrication and testing of a GaAs-based high-speed resonant cavity enhanced (RCE) Schottky photodiode. The top-illuminated RCE detector is constructed by integrating a Schottky contact, a thin absorption region ($In_{0.08}Ga_{0.92}As$) and a distributed AlAs–GaAs Bragg mirror. The Schottky contact metal serves as a high-reflectivity top mirror in the RCE detector structure. The devices were fabricated by using a microwave-compatible fabrication process. The resulting spectral photo response had a resonance around 895 nm, in good agreement with our simulations. The full-width-at-half-maximum (FWHM) was 15 nm, and the enhancement factor was in excess of 6. The photodiode had an experimental setup limited temporal response of 18 ps FWHM, corresponding to a 3-dB bandwidth of 20 GHz.**

***Index Terms*—High-speed circuits/devices, photodetectors, photodiodes, resonant caity enhancement, Schottky diodes.**

I. Introduction

HIGH-SPEED, high-efficiency photodetectors play an important role in optical communication and measurement systems. The high-speed properties of Schottky photodiodes have already been shown with reported 3-dB operating bandwidths exceeding 200 GHz [1]–[4]. However, the efficiency of these detectors have been limited, mostly due to the thin absorption region needed for short transit times. One can increase the absorption region thickness to achieve higher efficiencies. But this also means longer transit times which will degrade the high-speed performance of the devices. Resonant cavity enhanced (RCE) photodetectors potentially offer the possibility of overcoming this limitation of the bandwidth-efficiency product of conventional photodetectors [5]–[8]. The RCE detectors are based on the enhancement of the optical field within a Fabry–Perot resonant cavity. The increased field allows the usage of thin absorbing layers, which minimizes the transit time of the photo-carriers without hampering the quantum efficiency. High-speed RCE photodetector research has mainly concentrated on using p-i-n type photodiodes, where near 100% quantum efficiencies along with a 3-dB bandwidth of 17 GHz have been reported [9]. There are only a few reports on RCE Schottky photodiodes, where a 2-fold enhancement has been observed for RCE InGaAs–InAlAs based Schottky photodiodes [10]. In this letter, we report our work on design, fabrication and testing of high-speed RCE Schottky photodiodes for operation at 900 nm. We used the Schottky metal contact as a high-reflectivity top mirror in the RCE structure.

Manuscript received December 3, 1996. This work was supported in part by the Office of Naval Research under Grant N00014-96-1-0652, in part by the Turkish Scientific and Technical Research Council under Project EEEAG-156, and in part by the National Science Foundation International Collaborative Research under Grant INT-9601770.

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Publisher Item Identifier S 1041-1135(97)03236-9.

II. Design and Fabrication

We used an S-matrix method to design the epilayer structure of the RCE Schottky photodiodes. The structure was optimized for top-illumination and it consisted of a bottom Bragg mirror integrated with a Schottky diode structure. The mirror was formed by 15-pair AlAs(755 Å)–GaAs(637 Å) quarter wave stack designed to operate at 900 nm. The Schottky diode region had a 0.630 μm thick N^+ ($N_D = 3 \times 10^{18}$ 1/cm^3) layer for ohmic contacts, and a 0.3-μm thick N^- ($N_D = 1.2 \times 10^{17}$ 1/cm^3) region for the generation and transport of photo generated carriers. The N^- region consisted of a 1300-Å-thick photo active $In_{0.08}Ga_{0.92}As$ region, sandwiched between two GaAs N^- layers. The top GaAs N^- layer between the Schottky metal and the $In_{0.08}Ga_{0.92}As$ region had a thickness of 500 Å, while the other N^- region had a thickness of 1200 Å. The photo active $In_{0.08}Ga_{0.92}As$ region was placed closer to the metal contact in order to equalize the transit times of photo generated electrons and holes. The $In_{0.08}Ga_{0.92}As$–GaAs interfaces were graded to avoid electron and hole trapping. The total length of the cavity was designed to get the resonance to occur at 900 nm.

The epitaxial layers are grown by a solid-source MBE on semi-insulating GaAs substrates. We fabricated the epitaxial wafers using a monolithic microwave-compatible fabrication process. A cross section of the fabricated photodiodes is shown in Fig. 1. First, ohmic contacts to the N^+ layers were formed by a recess etch through the 0.3 micron N^- layer. This was followed by a self-aligned Au–Ge–Ni liftoff and a rapid thermal anneal. The semi-transparent Schottky contact was formed by deposition of 200 Å Au. Using an isolation mask, we etched away all of the epilayers except the active areas. Then, we evaporated Ti–Au interconnect metal which formed coplanar waveguide (CPW) transmission lines on top of the

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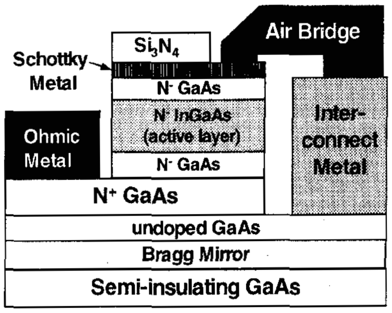

Fig. 1. Diagram showing the cross section of a fabricated RCE Schottky photodiode.

semi-insulating substrate. The next step was the deposition and patterning of a 2000-Å-thick silicon nitride layer. The thickness of the silicon nitride layer was chosen to act as an anti reflection coating for the RCE Schottky photodiode at the design wavelength. Besides passivation and protection of the surface, the silicon nitride was also used as the dielectric of the metal–insulator–metal bias capacitors. Finally, 1.5-μm-thick Au layer was used as an air bridge to connect the center of the CPW to the top Schottky metal [11]. The resulting Schottky diodes had breakdown voltages larger than 12 V. The dark-current of a 150 × 150 μm device at −1 V bias was 30 nA. Using the forward current–voltage characteristics, we measured the barrier height of the Schottky junction to be 0.83 eV.

III. Measurements

For spectral photo response measurements, we used a tungsten lamp source with a 1/3-m grating monochromator. The monochromatic light was delivered to the devices by a multimode fiber and the electrical characterization was carried out on a probe station. The spectral response was corrected by measuring the light intensity at the fiber output by a calibrated optical power meter. Overall error is expected to be within several percent. For photo spectral measurements, we used a 150 × 150 μm photodiode biased at −2.0 V. The photo response of the device obtained by using the aforementioned set up is shown in Fig. 2(a). For comparison purposes, the simulated quantum efficiency of the epitaxial structure is shown in Fig. 2(b). There is a reasonable agreement between the calculated and the measured spectral responses. The resonant wavelength of the device is 895 nm, which is very close to the design wavelength of 900 nm. When compared with a single-pass structure, the enhancement factor of the device is in excess of 6 at the resonant wavelength. The full-width at half maximum was 15 nm, corresponding to a ~1.6% spectral width. Although we predicted a peak quantum efficiency of 70%, the measured peak quantum efficiency was around 18%. The discrepancy between the experiment and simulation is due to the shift of the Bragg mirror center wavelength during the MBE growth, which resulted in a 60% bottom mirror at 900 nm.

High-speed measurements were made with short optical pulses of 1.5-ps FWHM at 895 nm wavelength. The optical pulses from the laser were coupled into a single-mode fiber,

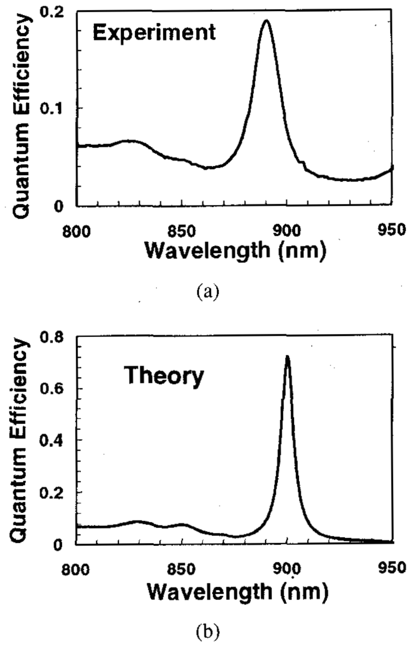

Fig. 2. (a) Measured photoresponse of RCE photodiode and (b) simulated photoresponse of the same structure.

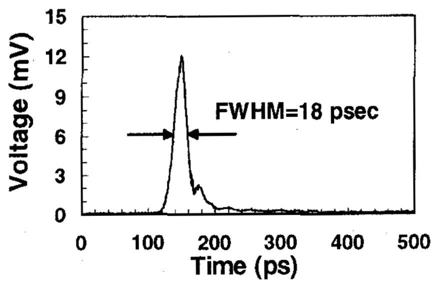

Fig. 3. Pulse response of RCE Schottky photodiode.

and the other end of the fiber was brought in close proximity of the photodiode by means of a probe station. We used a 8 × 9 μm device biased at −2 V, and the photodiode output was measured by a 50 GHz sampling scope. Fig. 3 shows the measured photodiode output which had a FWHM of 18 ps, and a fall-time of 20 ps. There is no residual photo current after the pulse fall-time (except the smaller bumps due to reflections from the electrical contacts) which indicates that there is no diffusion component which may limit the bandwidth of the device. This is in accordance with our expectations, as the photo active region is totally depleted, and the other regions are transparent at the resonant wavelength [6]. The Fourier transform of the measured output had a 3-dB bandwidth of 20 GHz. The symmetrical shape of the temporal response suggested that the measurement was limited by the experimental setup. Considering the measurement setup limitations, and the dimensions of the device under test, we estimate the actual temporal response of the device to be around 5.0 ps.

IV. Conclusion

We have demonstrated an RCE Schottky photodiode for operation at 900 nm. The full width at half maximum was

15 nm, and the enhancement factor was in excess of 6. The photodiode had an experimental setup limited temporal response of 18 ps FWHM, corresponding to a 3-dB bandwidth of 20 GHz.

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