High Bandwidth-Efficiency RCE Photodiodes Operating at 800-850 nm Wavelength

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Short-distance optical communications have a growing demand for fast and efficient photodetectors to complement vertical-cavity surface-emitting lasers (VCSELs) in the 800-900 nm wavelength range. VCSELs have emerged as the preferred sources owing to their tunability and high modulation-bandwidth.[1,2] For conventional top illuminated photodiodes (PD) the bandwidth-efficiency (BWE) product is limited by the material properties.[3] Resonant cavity enhanced (RCE) photodiodes allow for bandwidth-efficiency products beyond the conventional limits.[4] We have demonstrated RCE Schottky PD with bandwidths up to 100 GHz at 900 nm wavelength[5] and recently fabricated RCE pin photodiodes with 50 GHz BWE products.[6] We present an overview of our high-speed RCE photodiode work and discuss our recent studies of RCE pin photodiodes with nearly unity quantum efficiencies and more than 50 GHz bandwidths.

Figure 1 depicts the cross-section of the RCE pin PD. The epilayer structure was grown by solid-source molecular beam epitaxy on a semi-insulating GaAs substrate. An $Al_{0.2}Ga_{0.8}As/GaAs$ pin detector is placed in a low loss Fabry-Perot resonator formed by the semiconductor-air interface as the top mirror and a distributed Bragg reflector (DBR) as the bottom mirror. The DBR mirror consists of 24 quarter-wave stacks of $Al_{0.2}Ga_{0.8}As/AlAs$. Its stop band is designed for > 99% reflectance in a 40 nm wavelength window centered around 820 nm. The active layer is 470 nm of intrinsic GaAs. The interfaces between the absorption

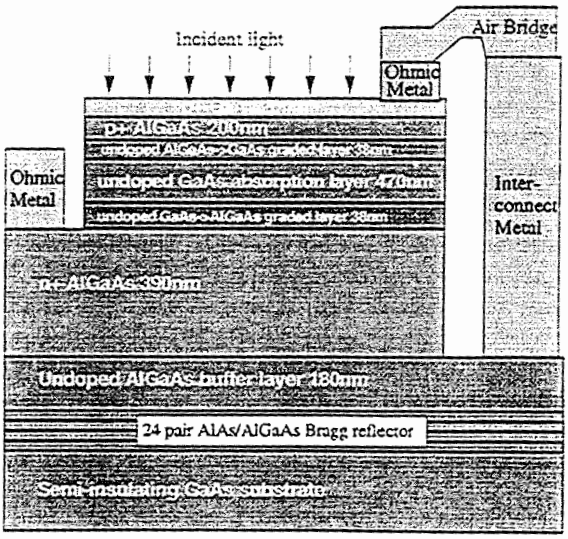

Figure 1. The schematic cross-section of the device reveals the epilayer and contact structure.

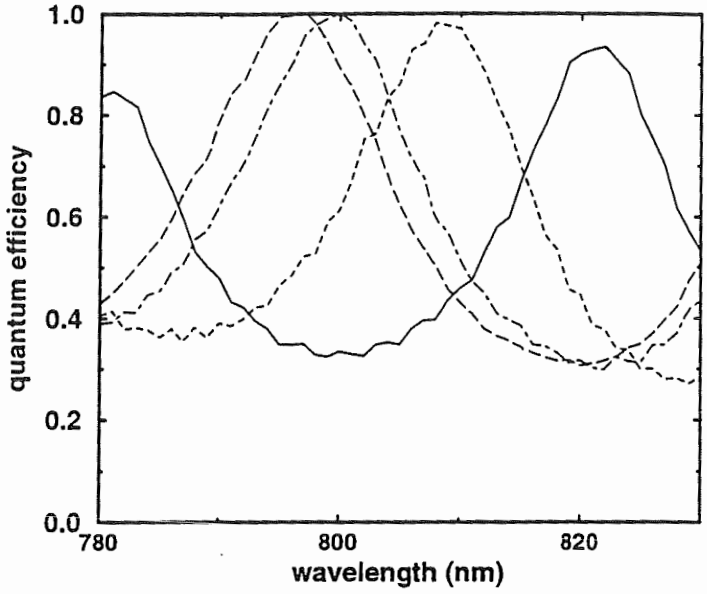

Figure 2. The resonance wavelength shifts toward shorter wavelengths as the top surface is recessed. The η of as-grown wafer is sub-unity (solid line), because the optical absorption in the GaAs cap layer does not contribute to the photocurrent.

layer and the doped regions are alloy-graded to avoid carrier trapping. The thickness is chosen according to the optimization: $R_{top} = R_{bottom}\exp(-2\alpha d)$.[4] We used scattering-matrix methods to calculate the reflectance and quantum efficiency of our designs. The measured reflectance of the as-grown structure agrees with the theoretical prediction within $\sim$ 1% thickness variation in growth. The devices were fabricated by a microwave-compatible process described elsewhere.[5] To optimize high-speed performance, we formed coplanar waveguides on the substrate and airbridges made of 1 μm thick Au connect the center of the waveguides to the ohmic contacts. The breakdown voltages of the photodiodes were over 14 V. The dark current in a device of 30 μm in diameter was 20 pA.

To characterize quantum efficiency we used a tunable continuous wave Ti:sapphire laser and single mode fibers for light delivery onto the detectors. In Fig. 2, we plot the measured quantum efficiency of a 250 μm $\times$ 250 μm detector, that exhibits nearly unity η at 800 nm. The accuracy of our measurements on large area devices was $\pm$2% and was only limited by the responsivity data (supplied by the manufacturer) of the NIST-traceable detector used to calibrate the setup. This figure also demonstrates the tunability of our devices after the fabrication by slow recess etches. The peaks preserve their finesse and efficiency along the tuning range determined by the stop band of the bottom mirror.

High-speed measurements were carried out in time domain, on a microwave probe station with a 50 GHz sampling oscilloscope using a mode-locked picosecond Ti:sapphire laser as the excitation. We plot the normalized responses of several devices with varying sizes in Fig.3. The smallest devices (14 μm $\times$ 8 μm) exhibited the fastest response governed by the transit time in the absorption region. The temporal response is 12 ps full-width-at half-maximum (FWHM). The measurement of these devices were limited by the speed of the sampling oscilloscope. When the response of the setup response is deconvolved, the estimated 3-dB bandwidth is more than 50 GHz. For larger devices, the depletion capacitance is appreciable. The depletion capacitance is 0.25 fF/μm^2 corresponding to a f_{3dB-RC} of 10 GHz for a 40 μm $\times$ 40 μm device with R = 50 Ω. The temporal responses were independent of the external bias and the results are shown for zero bias. We deduce that the intrinsic absorption region is fully depleted with built-in voltage. Hence, the photogenerated carriers are collected by drift and no diffusion process is involved in the response.

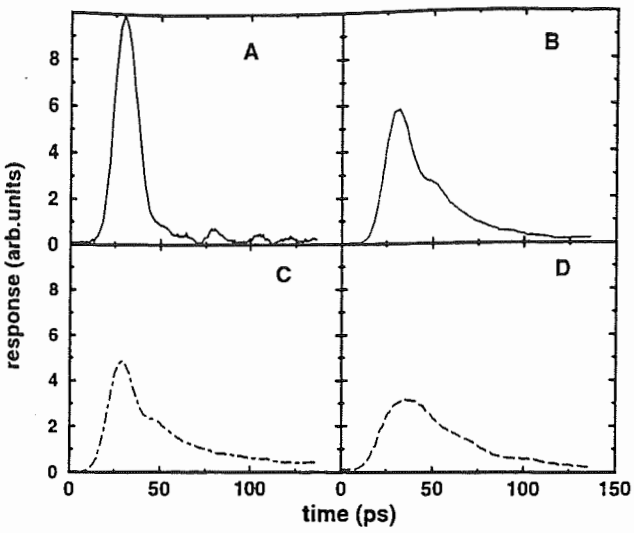

Figure 3. High speed responses from small and large devices. An RC tail evolves as the active area gets larger. A: 14 μm $\times$ 8 μm, and the diameters of the round detectors B, C, D are 30 μm, 60 μm, and 100 μm respectively.

In conclusion, we designed, fabricated and characterized high-speed RCE photodiodes with near-unity quantum efficiency. The bandwidth-efficiency products of the detectors are in excess of 50 GHz. The resonance wavelengths were post-process adjustable in the spectral region 780-830 nm. Picosecond temporal response combined with adjustable-wavelength near-unity η makes these RCE detectors suitable for quantum optical experiments especially those with pulsed lasers as well as for short-distance communication systems. Since the response speed is governed by transit time and capacitance charging time, large area devices also exhibit fast response.

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