Temporal and Spectral Characteristics of Back-Illuminated InGaAs Metal–Semiconductor–Metal Photodetectors

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Abstract— **We report dramatic differences in the impulse response and wavelength dependence of back versus top illuminated $In_{0.53}Ga_{0.47}As$ planar metal-semiconductor-metal devices. Via direct measurement of transit-time limited devices we identify the mechanisms involved and thereby allow the optimum design of multi-Gbit, high responsivity back-illuminated devices. We show that responsivities greater than 0.8 A/W are achievable with >8 GHz bandwidth for 50-μm-diameter devices.**

I. Introduction

InP–InGaAs based photodetectors for operation in high-speed fiber-optic communication systems continue to receive considerable interest. Planar metal-semiconductor-metal (MSM) structures exhibit intrinsically lower capacitance than similar-sized vertical p-i-n structures and consequently it has been shown that, for some applications, the MSM structure provides superior overall performance to the p-i-n detector [1]. Recently it has been shown that poor voltage performance may be overcome by careful attention to growth conditions and the substrate buffer layer composition [2]. Also, acceptable contact barrier heights are achieved using larger bandgap Schottky enhancement layers.

The inherent low responsivity of conventional planar MSM's is avoided using back illumination [3]. However, back illumination has been associated with reduced bandwidth when compared to top illumination [4]. Although other studies of capacitance-limited devices did not observe this bandwidth reduction [5].

In this letter we report the results of a detailed study of the bias voltage and wavelength dependence on the performance of an InGaAs-based MSM structure previously shown to be transit-time limited at low biases [2]. We directly compare the traditional top illumination condition with back illumination and find dramatic differences in both the impulse response and the wavelength dependence in the 1.36 μm to 1.55 μm regime. Using Fourier analysis we show that although there is bandwidth degradation in the back-illuminated case, multi-Gbit performance is maintained. In addition, we report on the bias and wavelength dependence of the responsivity increase seen under back illumination and show that responsivities greater than 0.8 A/W are achievable with >8 GHz bandwidth.

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II. Structure

The devices reported in this paper consist of a 100 nm AlInAs buffer layer grown by molecular beam epitaxy on a InP:Fe substrate followed by a 1.0 μm thick $In_{0.53}Ga_{0.47}As$ light absorbing layer. A graded Schottky enhancement layer consisting of $In_{0.52}Al_{0.48}As$ completed the structure. Each of the layers was lattice-matched and nominally undoped. The devices were composed of interdigitated 1 μm-wide electrodes with a spacing of 2.0 μm and had an active area diameters of 50 and 100 μm. The results reported here rely on standard contact photolithography and do not require the use of nanofabrication techniques which have been shown to produce exceptionally high-speed devices in the GaAs material system [6]. For the back illumination studies, the substrate was mechanically thinned to <200 μm, chemically polished and antireflection coated with SiN_x to provide specular reflection.

Near-infrared 150 femtosecond duration pulses were obtained from an optical parametric oscillator which was tunable from 1.35 μm to 1.6 μm.[1] Accurate comparisons of the top versus back substrate illumination responses were achieved employing a silicon "waferboard" which had V-grooves and reflectors etched in the top surface. The V-grooves permanently positioned single-mode fibers to illuminate the reflectors. Individual devices were placed above the reflectors with the polished substrate in contact with the silicon surface. For top illumination, a single-mode fiber was positioned directly above the device. The devices were electrically contacted via a 26 GHz coplanar microwave probe, cable and bias-Tee assembly. The photocurrent was measured using a digital sampling oscilloscope with a bandwidth-limited risetime of 17 ps. The measured pulse-to-pulse jitter was typically 600 fs.

[1] We thank Spectra-Physics Lasers, Inc., for the loan of the femtosecond optical parametric oscillator.

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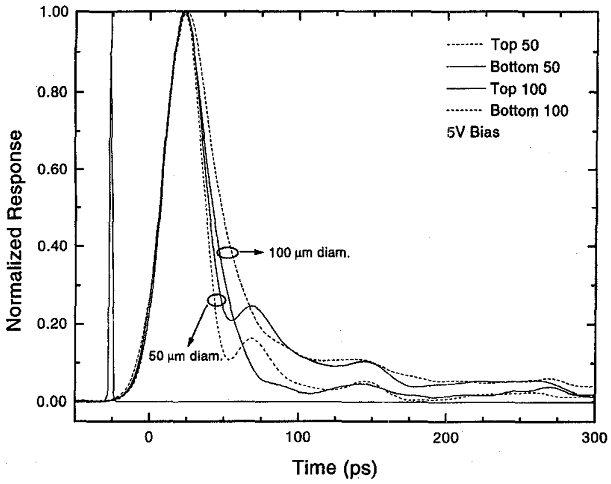

Fig. 1. The impulse response for back and top illumination of a 50- and 100-μm-diameter planar MSM detector biased at 5 V. The incident pulse width is portrayed near $t = -25$ ps. For both devices an enhanced tail component is observed when back illuminated.

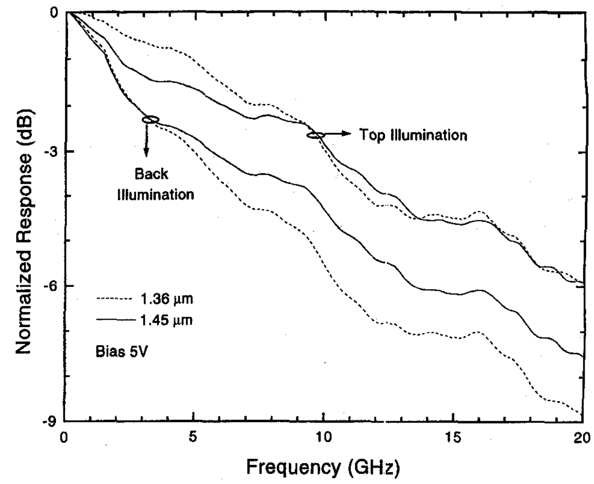

Fig. 2. Frequency response via Fourier analysis at 5 V bias for both top and back illuminations at two wavelengths, $\lambda = 1.36$ and 1.45 μm. The data are normalized todisplay the bandwidth differences due to both illumination technique and wavelength.

The dark current for the devices reported here ranged from 1 nA at 5 V to 8 nA at 10 V bias.

III. Results

Fig. 1 depicts the normalized impulse response for both top and back illumination for 50- and 100-μm-diameter devices illuminated with 20 μW (0.25 pJ/pulse) at a wavelength of 1.36 μm. All the results reported here are typical of more than 20 devices measured. A 5 V bias was chosen for illustration to demonstrate the performance of these MSM's at desired system operating voltages. The devices were found to behave linearly at optical powers up to 500 μW. Consider first the 50-μm-diameter devices which are transit time limited. The back illumination case shows a significantly enhanced secondary decay component ($t > 50$ ps) attributed to holes and is systematically larger for the back illumination case. This enhanced tail component occurs for all illumination wavelengths, intensities and applied biases measured. Indeed, this effect is also clearly noticeable with larger area devices (100 μm) which are not fully transit-time limited. These effects may not be observable in slower RC-limited devices [5]. Screening effects were eliminated by using low incident power. These observations are understood by considering that electrons maintain velocity saturation for biases greater than two volts [7]. In contrast, the slower holes rarely reach saturation velocity within the structure. Thus when carriers are photogenerated further from the electrodes, as in back illumination, the longer transit times in regions of low field produce this enhanced tail component. The long tail component is sensitive to bias and wavelength via the initial spatial distribution of the photogenerated charge.

In contrast to changes in the tail component, the measured pulse widths of the main peaks for 50 μm devices are similar, 26 ps top versus 28 ps back. This corresponds to a deconvolved full-width-half-maximum (FWHM) of 17 ps for top and 19 ps back illumination. This illustrates the need for a proper Fourier analysis to understand the effects on bandwidth. The normalized Fourier transforms of temporal responses at 5 V bias are shown in Fig. 2. The data have been corrected for losses (not reflections) due to the electrical measurement setup.[2] Although Fourier analysis of the impulse response produces systematically different bandwidth results as compared to direct frequency measurements, this approach yields valid relative bandwidth results and allows the determination of the physical origin of the bandwidth-limiting phenomena. Understanding these limitations allows proper tradeoffs to be made in the design of a useful detector.

Fig. 2 illustrates that top illumination produces a markedly higher bandwidth than its back illumination counterpart, irrespective of the incident wavelength. The wavelength dependence also reveals the importance of the initial carrier spatial distribution. For the top illumination case, the lower frequencies (<5 GHz) exhibit an enhanced response for shorter wavelengths due to the shallow absorption depth and the subsequent generation of carriers in close proximity to the electrodes. The slower response of the back illumination case is also attributable to carriers being generated in the region underneath the electrodes, where transit times are dramatically longer for the carriers to make their way to the opposite electrode. At higher frequencies the responses are similar, due to electrons being the predominant carrier responsible for the photocurrent at short transit times. For the back illumination case, holes and electrons are generated further away from the high field region when illuminated at shorter wavelengths. Thus, due to the absorption depth difference, the longer wavelengths ($\lambda = 1.4$, 1.5 μm) exhibit higher bandwidths for the back illumination condition.

This trend also holds true regardless of bias, as shown in Fig. 3. Overall, the back illumination bandwidth shows a decrease of about 50% as compared to the top illumination condition, which was also reported by Kim, et al. [4]. The

[2] Electrical frequency measurements of the cable, bias-tee, and probe were made on a network anaylyzer and removed numerically from the Fourier transform of the impulse response.

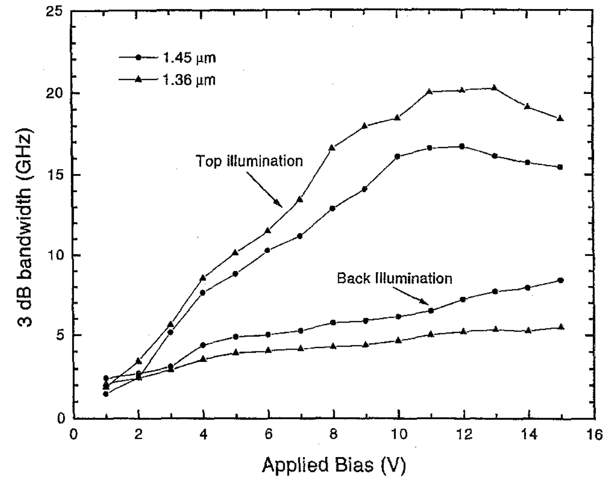

Fig. 3. Bias dependence of the 3-dB bandwidth at $\lambda = 1.36$ and 1.45 μm for both top and back illumination conditions.

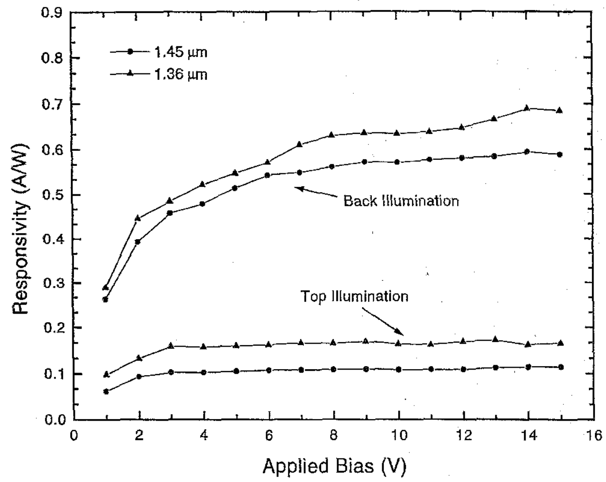

Fig. 4. Measured ac responsivity as a function of bias for $\lambda = 1.36$ and 1.45 μm. Both top and back illumination conditions are shown. The responsivity has been corrected for optical and electrical system loss.

downturn in bandwidth for high biases (>11 V) in the top illumination case may be explained by noting that at these biases the average field strength is substantially higher than the electron peak-velocity field strength. Thus high biases result in slower electron velocities and reduced bandwidth [8], [9]. The back illumination case does not exhibit this downturn in bandwidth at high bias, since the hole transport time is the bandwidth-limiting mechanism. Hence bandwidth continues to increase with bias. Reducing the absorbing channel thickness will markedly improve the back illumination bandwidth, but will produce smaller improvements for the top illuminated case. A four channel receiver, incorporating 100-μm-diameter devices and 1.5 GHz transimpedance amplifiers exhibited no errors at 1.4 Gb/s with clean open eye diagrams under moderately high optical powers and a sensitivity of -26 dBm at a BER of 10^{-9} at 1 Gb/s [10]. The word length for these measurements was $2^{23}-1$ (PN23) with a NRZ format.

Fig. 4 shows the ac responsivity as a function of bias. The top illuminated responsivity curves are nearly independent of bias and are expectedly lower ($\approx$0.2 A/W) than their dc counterparts (0.35 A/W). Again, since most of the carriers are generated near the electrodes where the material is readily depleted at fairly low (<5 V) bias and regions behind the electrodes are void of carriers. Hence the top-illumination responsivity is not a strong function of bias. The back illumination case exhibits a responsivity of nearly 0.7 A/W for $\lambda = 1.36$ μm, close to its dc value of $\approx$0.8 A/W. Here the responsivity is a stronger function of bias than its top illumination counterpart, due to the low average field strength at the back of the absorbing channel. Additionally back illumination may result in photogeneration of carriers outside the active area of the device. These carriers may eventually be collected, thus improving the dc response; however, it is likely that some of the carriers recombine before they can be collected. The wavelength differences are attributed to the difference in absorption for the material.

IV. Summary

In summary, we have measured the bias- and wavelength-dependence of back-illuminated InGaAs MSM's. Via Fourier analysis, we have shown that the power bandwidth is quite sensitive to wavelength for the back illumination case. This was explained by the wavelength-dependence of the absorption depth for the incident light along with the long transit length of carriers in the back region far from the electrodes. In spite of the bandwidth degradation seen for back illumination, the MSM's are still capable of achieving multi-Gbit data-rates at low biases, with a high responsivity.

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[10] Results to be published elsewhere.