2.0 ps, 150 GHz GaAs Monolithic Photodiode and All-Electronic Sampler

E. Özbay, K. D. Li, and D. M. Bloom

***Abstract*—An ultrafast GaAs Schottky photodiode is monolithically integrated with an all-electronic sampler. The high-speed photodiode-electronic-sampling circuit has a temporal response of 2.0 ps full-width-at-half-maximum (FWHM) corresponding to a 3-dB bandwidth of 150 GHz. The photodiode has an external quantum efficiency of 33%. To our knowledge, this is the fastest photodiode ever reported.**

INTRODUCTION

HIGH-SPEED photodetectors play an important role in optical communication and measurement systems. In a communication system, the use of faster detectors could enhance the system bandwidth, increasing information transmission capacity. In a measurement system, they could replace autocorrelation and cross-correlation techniques which require deconvolution methods since the pulse waveform is not directly measured. In order to make high-bandwidth or equivalently high temporal-resolution measurements, it is essential to have high-speed photodetectors with good responsivity. Photodetectors are made from many different materials, but only GaAs and InGaAs devices have been used as high-speed detectors. GaAs devices are sensitive only for wavelengths shorter than 890 nm. For longer wavelength high-speed applications, InGaAs photodetectors are used. Wang and Bloom [1] were the first to demonstrate a GaAs photodiode with a 3-dB bandwidth exceeding 100 GHz and a temporal response of 5.4 ps. Later, Parker *et al.* [2] succeeded in achieving up to 110 GHz performance. For InGaAs photodetectors, Wey *et al.* [3] reported a 3.8 ps FWHM. In addition, they reported the hybrid integration of their InGaAs photodetector and GaAs sampling circuit. All these results have been limited by their measurement techniques. The speed of the actual device had to be indirectly determined by a deconvolution of the system response from the measured data.

In order to overcome these measurement problems, we have pursued a monolithic approach [4], [5]. A GaAs based all-electronic sampler is monolithically fabricated with a high-speed Schottky photodiode. Without deconvolution, we are able to measure a temporal response of 2.0 ps FWHM, corresponding to a 3-dB bandwidth of 150 GHz.

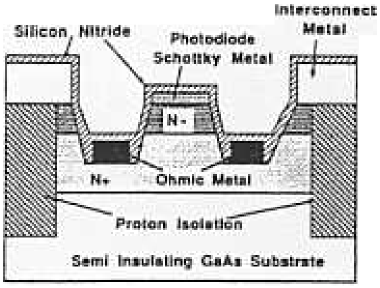

Fig. 1 Diagram showing the cross section of the 5 × 5 μm^2 semi-transparent Schottky photodiode.

PHOTODIODE AND SAMPLER DESIGN

Because the fabrication technologies for 290 GHz bandwidth GaAs samplers [6] and 100 GHz Schottky photodiodes are very similar, it is a simple step to combine the two devices. Using the same process technology, we designed our device to incorporate the photodiode, sampler and strobe nonlinear transmission line (NLTL) on the same chip. Our samplers were fabricated on MBE-grown GaAs with a 0.3 μm thick N^- active layer (1.2×10^{17} cm^{-3} doping) on top of a 0.8 μm N^+ highly conductive layer (3×10^{18} cm^{-3} doping).

Photodiodes were then fabricated by using the top N-layer as the depletion region. The relatively heavy-doping of this layer results in a punch-through voltage of 6.7 V. This large punch-through voltage enables us to vary the thickness of the photoactive region by simply changing the bias voltage. Due to the high-doping in the N^- region, the additional series resistance from the undepleted N^- layer is negligible. For our 5 × 5 μm device, this additional series resistance is typically 1 to 2 Ω. Thus, in our diode, the transit time of the electrons through the active region as well as the capacitance of the diode may be varied electrically. For a given photodiode area and assumed carrier velocities, it is well known that there is an optimum thickness for the active region, for which the transit time and *RC* time constant are comparable. Our biasing scheme allows us to operate the device at the electronically achievable optimum depletion width.

A cross section of our Schottky photodiode is shown in Fig. 1. First, ohmic contacts to the N^+ layer are formed by a recess etch through the 0.3 μm N^- layer followed by a self-aligned Au-Ge-Ti liftoff and a rapid thermal anneal.

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The authors are with the Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305.

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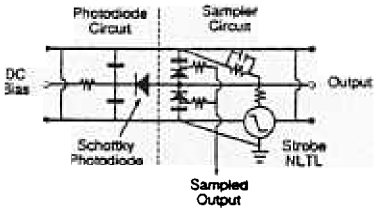

Fig. 2. Circuit schematic of the photodiode, sampler and nonlinear transmission line (NLTL) strobe.

Next, proton implantation is used to define our active regions as well as to convert the rest of the epilayers to semi-insulating material. 100 Å of gold are then deposited over the photoactive region to make the semitransparent Schottky contact. This last step is the only additional photolithography step that is needed for monolithic integration of the sampler and photodiode. Finally, interconnect metal and silicon nitride are deposited. We chose the thickness of the silicon nitride layer to act as an antireflection coating for the Schottky photodiode. Bias capacitors with relatively large capacitances with respect to the photodiode are easily incorporated into the circuit by reverse biasing the Schottky diodes formed in the active regions under the interconnect metal. Choosing a large capacitor value results in dc bias stabilization as long as the total charge that is discharged from the photodiode is relatively small.

The circuit schematic of the monolithic photodiode-sampler is shown in Fig. 2. The output of the photodiode is connected to the sampler through a coplanar transmission line. The step-like waveform produced by the NLTL strobe is differentiated by the shorted transmission lines, resulting in a voltage pulse across the sampler diodes. This turns on the sampling diodes for the duration of this electrical pulse and enables the sampling capacitors to sample the photodiode signal on the transmission line. The sampled signal is then filtered out by using resistors. The photodiode signal which propagates further on the transmission line can be either terminated by a 50 Ω resistor or extracted through bond wires or microwave probes.

HIGH-FREQUENCY MEASUREMENTS

Pulses from a Spectra Physics Nd:YAG mode-locked laser were compressed in a fiber-grating compressor and frequency-doubled in a KTP crystal before they were used to excite our photodiode-sampler circuit. The laser was mode-locked at 82.16 MHz and produced 50 ps FWHM pulses. After compression, the pulse duration was 1.6 ps, producing 1.1 ps durations at 532 nm. The optical pulses then were focused on the photodiode. Sampling of the photodiode was done at the 50th harmonic of the mode-locker frequency with a 10 Hz offset. This oversampling reduced the sampler output by a factor of 50. A buffer amplifier with a voltage gain of 35 was used at the output of the sampler to increase its IF bandwidth. The resulting equivalent time waveform had a period of 100 ms, which corresponded to 242 ps in real time.

The sampled output of the photodiode signal is shown in Fig. 3. By changing the reverse-bias voltage, we found the minimum device response, or for our photodiode layout, its optimum depletion width, at 4.5 V. This corresponds to a 0.25 μm depletion region. At this bias voltage, we measured 2.0 ps FWHM pulses. At both higher and lower voltages, the pulse width increased. This is a direct measurement from the sampler. It corresponds to a total system response which includes contributions from the photodiode impulse response, the sampler aperture time, the laser pulse duration, the laser timing jitter (< 600 fs), and the microwave synthesizer jitter. When these effects are considered, we estimate the response of the photodiode to be about 1.5 ps. Given the 0.25 μm depletion width, this estimate yields an average carrier velocity of 1.7×10^7 cm/s, which may be indicative of velocity overshoot.

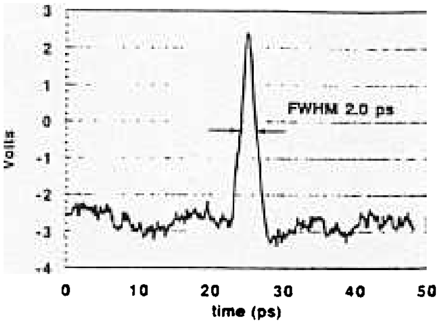

Fig. 3. Electronically sampled photodiode output.

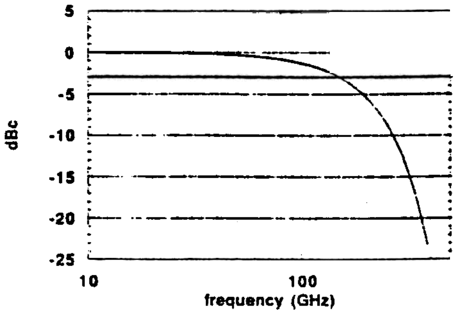

Fig. 4. Fourier transform of the data shown in Fig. 3.

The Fourier transform of the measured output without the baseline noise is shown in Fig. 4. The overall system response has a 3-dB bandwidth of 150 GHz. We measured a responsivity of 0.15 A/W which corresponds to an external quantum efficiency of 33% at 532 nm. Such high efficiency indicates an effective antireflection coating. The typical operating average photocurrent while using the sampler was kept below 2 μA which corresponds to a peak current density of 4.8×10^4 A/cm^2 or a peak voltage of 0.6 V into a 50 Ω load.

CONCLUSION

We have fabricated a monolithic photodiode-sampler. The total response of the system was measured to have a FWHM of 2.0 ps and a 3-dB bandwidth of 150 GHz. The external quantum efficiency is found to be 33%. To our knowledge, this device is the fastest photodetector.

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