2-picosecond, GaAs photodiode optoelectronic circuit for optical correlation applications

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An ultrafast GaAs Schottky photodiode is monolithically integrated with a microwave detector. By using this new optoelectronic circuit in place of a nonlinear crystal in an optical correlation setup, the high-speed photodiode can measure laser pulse durations without using expensive sampling oscilloscopes. Key advantages are that this circuit works over a broad wavelength range and at low peak optical powers. The correlated temporal response of the circuit is measured to be 1.9 ps full width at half maximum. Due to its wavelength flexibility, cross correlation with different lasers may be performed with this single device.

Since Schottky photodiodes have recently achieved 200 GHz bandwidths, or time resolutions of 1.8 ps,[1] they can be used to measure pulse durations of ultrafast lasers. In the past, ultrafast measurements with photodiodes necessitated the use of sampling oscilloscopes or complex, high-bandwidth measurement systems such as electro-optic sampling.[2–4] The problem of high-bandwidth photodiode measurements was recently addressed by monolithically integrating a high-speed all-electrical sampler with an ultrafast GaAs Schottky photodiode.[5,6] In effect, this is similar to placing the sampling head of a very fast (300 GHz) sampling oscilloscope on the same chip as the photodiode.

In this letter, we report a new optoelectronic circuit which consists of a high-speed photodiode monolithically integrated with a microwave detector. By using this circuit in place of a second harmonic generation (SHG) crystal in an autocorrelation setup, short optical pulses can be measured without requiring expensive sampling oscilloscopes, microwave synthesizers, or complex optical sampling systems. One advantage of the circuit over a wavelength-specific SHG crystal is that it is sensitive to all wavelengths with an energy greater than the semiconductor band-gap energy. Thus, cross correlation with different laser sources is easily executable with a single device. With this photodiode/microwave detector circuit, we are able to measure a correlated 1.9 ps full width at half maximum (FWHM).

The photodiode and microwave detector are easily integrated using straightforward fabrication technologies. The photodiode adds only one mask step to the fabrication process for the microwave detector circuit. A cross section of our 3×3 μm^2 Schottky photodiode is shown in Fig. 1. The circuits were fabricated on molecular beam epitaxy (MBE)-grown GaAs with a 0.2 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). The top N^- layer provided the photodiode depletion region as well as the active layer for the microwave detector.

The device processing steps are described as follows. First, ohmic contacts to the N^+ layer are formed by a recess etch through the 0.2 μm N^- layer followed by a self-aligned Au/Ge/Ti lift-off and a rapid thermal anneal. 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, then we define the 1×5 μm^2 microwave detector diode and deposit gold for its Schottky metal. The next step is the deposition of the interconnect metal. Finally, using plasma-enhanced chemical vapor deposition (PECVD) silicon nitride is deposited. We chose the thickness of the silicon nitride layer to act as an antireflection coating for the Schottky photodiode. Bias capacitors are easily incorporated into the circuit by reverse biasing Schottky diodes formed in the active regions under the interconnect metal. Choosing a large value of capacitance results (>500 times the photodiode capacitance) in dc bias stabilization provided that the total charge that is discharged from the photodiode is relatively small.

The circuit schematic is shown in Fig. 2. The photodiode output signal travels a short distance along a transmission line to a second Schottky diode that serves as the microwave detector. For low-level input signals, the nonlinearity of the microwave detector's current-voltage characteristic produces a dc voltage that is proportional to the square of the applied rf signal from the photodiode.[7]

Using this circuit to replace the SHG crystal in an autocorrelation setup (Fig. 3), permits the measurement of laser pulse durations. The input light beam is split into two beams, and the two resulting pulse trains are delayed with

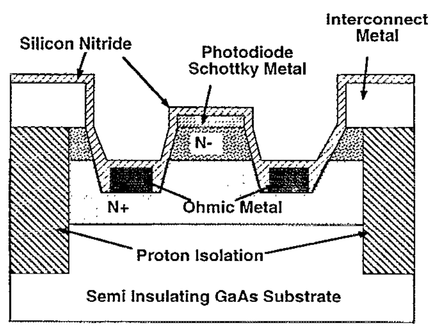

FIG. 1. Diagram showing the cross section of the 3×3 μm^2 semitransparent Schottky photodiode (reprinted from Ref. 5).

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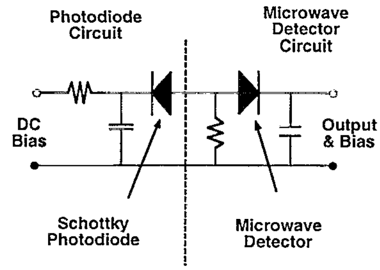

FIG. 2. Circuit schematic of the photodiode and microwave detector.

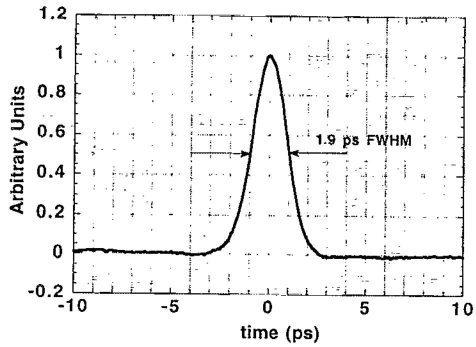

FIG. 4. Output of the photodiode and microwave detector correlation circuit, showing an autocorrelation trace. The FWHM of the correlated pulse if 1.9 ps.

respect to each other. They are then recombined on a beamsplitter and focused on the photodiode of the circuit. The photodiode output, which consists of voltage pulses from each leg of the setup, travels the short distance to the microwave detector. When the pulse trains do not overlap in time, the microwave detector's dc term is proportional to the sum of the squares of the peak voltages. However, when the pulse trains do temporally overlap, the dc term is proportional to the square of the sum of the peak voltages. Thus, if both pulse trains are of equal amplitude, the peak of the correlated microwave detector output will be twice the base line value, exactly analogous to autocorrelation performed with a SHG crystal.

To ensure correct overlap of the two paths on the 3×3 μm^2 photodiode, the variable delay arm had to provide vibration-free optical delays. This was achieved by using a retroflector with a fast scanner.[8] The compact, vibration- and backlash-free scanner consisted of a miniature crossed roller bearing slide propelled by a galvonometer (General Scanning G325DT). The scanner provided a total optical delay of 90 ps at 25 Hz.

Laser pules from a Spectra-Physics Nd:YAG mode-locked laser were compressed in a two-stage fiber-grating compressor and frequency doubled in a KTP crystal. The resulting 532 nm pulse used to excite the photodiode had a pulse duration of 300 fs. With a combined average power of 35 μW incident on the photodiode, the output of the circuit appears as shown in Fig. 4. Because output amplitudes were less than 1 mV, a preamplifier (PAR 113) was required. The FWHM of the correlated pulse is 1.9 ps, and assuming input Gaussian pulses, the actual photodiode

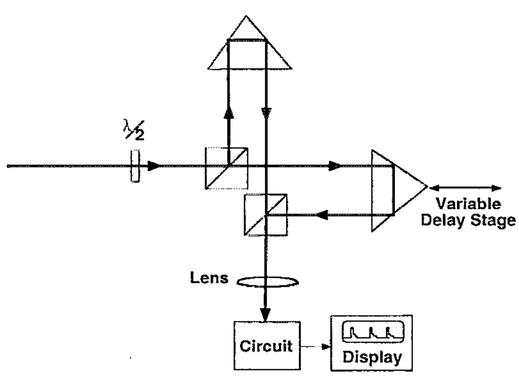

FIG. 3. Experimental setup for performing autocorrelation using the photodiode/microwave detector circuit.

output is 1.4 ps. The limiting factor to the temporal resolution of the circuit is the photodiode itself.

The photodiode and microwave detector were independently biased to achieve the best optical and microwave performance. The photodiode had a 0.15 A/W responsivity at 532 nm, and was biased so that the 0.2 μm N^- layer was fully depleted. The microwave detector bias was adjusted for optimum sensitivity and bandwidth performance. At 1.4 V, the microwave detector's sensitivity was 74 V/W for a sine wave input.

One of the main advantages of this circuit over a nonlinear crystal correlator is that unlike conventional autocorrelation techniques, which require a few watts of peak optical power, this device can measure low peak optical power. Four factors contribute to the noise of the microwave detector: the shot noise of the junction, the thermal noise of its series resistance, the thermal noise of the video amplifier, and the flicker noise of the diode. When all these are taken into consideration, we expect a tangential sensitivity (TSS) as low as -40 dBm. The TSS is the rf power level expressed in dBm at which the highest noise peaks in the absence of signal are at the same level as the lowest noise peaks in the presence of signal. In a 50 Ω system and with 0.15 A/W responsivity for the photodiode, this TSS corresponds to 20 mW of peak optical power or 3 μW of average power for an 82 MHz, 2 ps pulse train. Thus, this circuit can be used to measure the output of extremely low-power, pulsed lasers.

Due to the wavelength flexibility of this device, it is well suited for cross correlation applications. Since the photodiode is sensitive to all wavelengths with energies greater than the semiconductor band gap, different lasers can be used for the sampling pulses and the sampled pulse train.

In summary, we have fabricated a monolithic photodiode and microwave detector circuit. This circuit allows picosecond resolution autocorrelation and cross correlation to be performed at extremely low optical powers. In addition, because the photodiode is sensitive to all wavelengths with energies greater than the semiconductor bandgap, operation at many different wavelengths is easily achieved with one device.

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