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Coplanar vacuum photodiode for measurement of short-wavelength picosecond pulses

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We have fabricated a vacuum photodiode in a coplanar stripline geometry. This device is capable of high quantum efficiency and picosecond response time. It may be particularly useful for diagnostics of picosecond soft x rays from laser-produced plasmas.

A vacuum photodiode is the most elementary photoelectric detector. Photons impinge on a photocathode in vacuum. A nearby anode collects photoelectrons from the cathode and the resulting photocurrent is measured in a suitable external circuit. Such a device is sensitive to photon energies which exceed the photocathode work function in accord with the classical photoelectric effect. Photocathode materials with high quantum efficiency (1–30%) have been developed for use at optical wavelengths shorter than ~ 1 μm. For vacuum ultraviolet and soft x-ray radiation, photoelectric quantum yields in excess of 50% can be reached.[1] With a carefully designed external circuit, the response time of such a detector is limited by the diode capacitance. The present state-of-the-art rise time in a commercial biplanar vacuum photodiode[2] is 60 ps.

Recent studies[3] have demonstrated the utility of the coplanar transmission line geometry with lateral dimensions of several micrometers for the generation and propagation of picosecond electrical pulses. We have realized an ultrafast vacuum photodiode detector by taking advantage of a microfabricated coplanar stripline geometry. Two parallel electrodes themselves serve as the photocathode and anode. Due to the extremely wide circuit bandwidth, the speed of response of the photodiode is no longer limited by the circuit, but instead by the transit time of the photoelectrons in vacuum in the vicinity of the stripline electrodes. With a stripline spacing of a few microns, and a sufficiently high bias potential applied between the strips, the transit time can be in the range of a few picoseconds. In order to read out the ultrafast electrical waveform produced on the stripline, a conventional photoconductive sampler is used.

A representation of our initial devices is shown in Fig. 1. Gold striplines of 5 μm width separated by 5 μm were deposited on a silicon-on-sapphire substrate. Before the striplines were deposited, the silicon was etched off except in a 2-mm-wide strip in the region of the sampling gap so that in the photodiode area of the detector, no silicon remains between the strips. The gold lines were electroplated to a thickness of 1 μm under plating conditions chosen to yield a "roughened" surface in order to enhance the photoelectric yield. The remaining silicon was radiation damaged at room temperature using 2 MeV Ar^+ ions at a dose of 3×10^{15} cm^{-2}. This provided high-speed material for the sampling gap.[4] After mounting in a suitable fixture, the device was installed in a turbomolecular-pumped vacuum chamber with a base pressure of 2×10^{-6} Torr. A further increase in photoelectric yield was obtained by *in situ* evaporation of a few monolayers of cesium over the surface of the device, which decreased the photocathode work function.

In these first experiments, 266 nm ultraviolet (UV) laser pulses derived from a cw mode-locked Nd:YAG laser were used to investigate the performance of the photodiode. Pulses of 532 nm second-harmonic light from this laser were compressed[5] to <500 fs and used to trigger the sampling gap. The UV pulses were produced by subsequent second-harmonic generation using a 1-mm-thick beta-barium borate (BBO) crystal. Nearly 8 mW of UV was available. The UV pulse duration was not directly measured, but was estimated to be ~ 500 fs. The UV radiation was focused through a quartz window into the vacuum chamber onto the cathode strip. The focal spot diameter was slightly larger than 5 μm so that the entire width of the cathode strip was uniformly illuminated.

Representative results are shown in Fig. 2. The signal was confirmed as photoelectric in origin by venting the vacuum chamber with air and observing the signal disappear due to electron scattering by air molecules. The device was quite sensitive to UV radiation; even our crude cesiated gold photocathode was approximately an order of magnitude more sensitive than the radiation-damaged silicon photoconductor.

The signal fall time was found to decrease markedly as the applied cathode-anode bias voltage increased. The bias

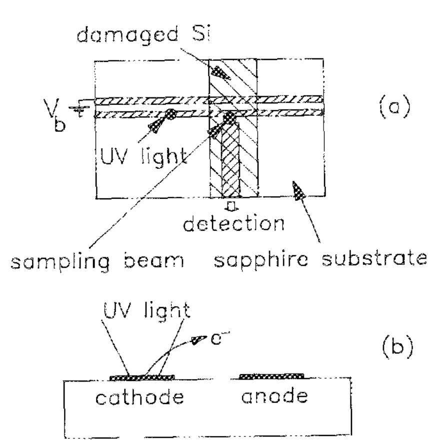

FIG. 1. Schematic diagram of the coplanar vacuum photodiode. (a) Top view, (b) side view.

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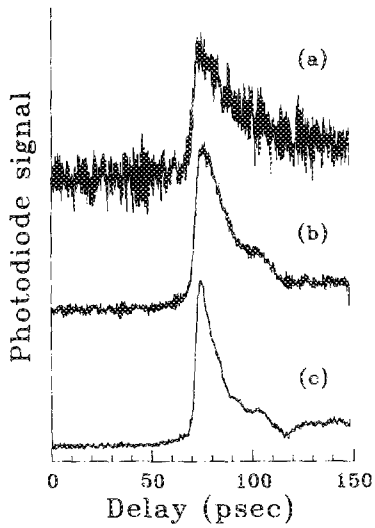

FIG. 2. Measured waveforms from the vacuum photodiode-photoconducting sampler device. (a) 5 V bias, 10–90% rise time: 6 ps, $1/e$ fall time: 36 ps. (b) 20 V bias, rise time: 5 ps, fall time: 20 ps. (c) 60 V bias, rise time: 4 ps, fall time: 12 ps.

voltage was applied to the anode with the cathode held at ground potential. With 60 V applied bias, we obtained a 4 ps rise time and a 12 ps fall time. It was not possible to apply a higher bias voltage to this device due to avalanche breakdown of the silicon between the lines. The dependence of the rise and fall times on applied bias is shown in Fig. 3. The rise time is seen to be essentially independent of bias while the fall times follows a $1/\sqrt{V_b}$ dependence, where V_b is the bias voltage applied between the strips. This is the expected behavior for electron transit time in a vacuum diode.[6]

As mentioned above, the cathode strip was uniformly illuminated over its 5 μm width. The UV spot size was not small enough to determine if there was any dependence in the pulse waveforms on position across the cathode strip from which the electrons were emitted.

In addition to the decreasing fall time with increasing bias, we observed a nearly linear increase in signal magnitude with increasing applied bias. We interpret this to be an indication that the emitted cathode current is influenced by space-charge effects. For a vacuum photodiode under constant illumination conditions, one expects the emitted current to increase with applied bias in the space-charge-limited regime, and then to saturate when all of the photocurrent is extracted from the cathode. Apparently, at the maximum applied bias of 60 V, saturation was not reached. We estimate the peak cathode current density to be in excess of 200 A/cm^2.

In order to gain a better understanding of what determines the response time of the device, the potential distribution and electron trajectories were calculated using an electron gun design program.[7] An example of the results is shown in Fig. 4. We see that, due to the large component of electric field normal to the surface of the cathode, the electrons travel out and away from the strips, rather than curving sharply back around to the anode. Even though the photoelectrons are not collected by the anode, a potential difference is induced between the cathode and anode, which is then sensed at the sampling gap. It is clear that the fall time of the pulse generated on the strips will be controlled by the flight time of the electrons through the near-field region. In order to estimate this, we calculated the time required for the

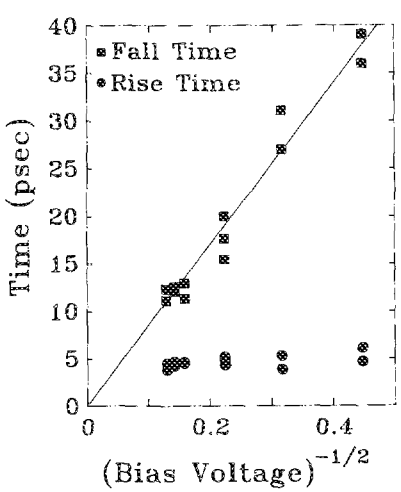

FIG. 3. Measured 10–90% rise times and $1/e$ fall times plotted against $1/\sqrt{V_b}$.

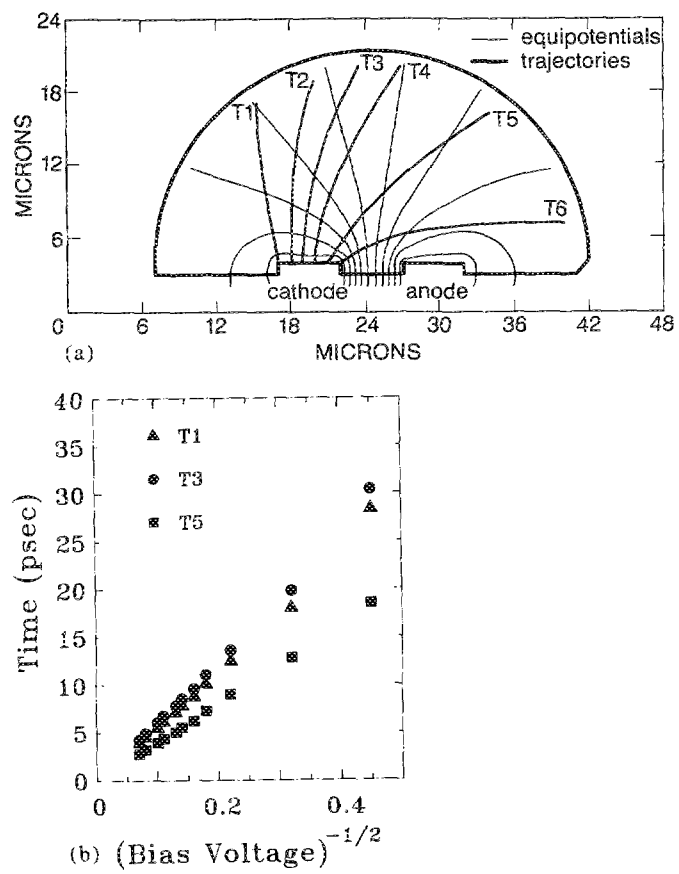

FIG. 4. (a) Calculated equipotentials and electron trajectories. The equipotentials are drawn at $0.05V_b$, $0.15V_b$, $0.25V_b$,...,$0.95V_b$. Six examples of the electron trajectories are shown labeled $T1$, $T2$,...,$T6$ for identification. (b) Calculated transit times to the boundary for three of the example trajectories. The calculated transit times for the other trajectories fall between those shown here.

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electrons to reach the cylindrical boundary shown in Fig. 4(a), which was somewhat arbitrarily drawn at a radius of 18 μm from the midpoint between the strips. The results for several different trajectories are shown in Fig. 4(b) as a function of the applied bias voltage. The calculated flight times do very nearly follow a $1/\sqrt{V_b}$ dependence, and nearly agree quantitatively with the measured fall times. We therefore conclude that the fall time of the pulse on the strips is determined by the transit time of the photoelectrons out to a distance of several times the strip spacing.

In order to consider the influence of the space-charge field on the electron transit times, we repeated the above calculations with the emitted cathode current automatically set by the Child-Langmuir law.[6] These transit times were virtually identical to those shown in Fig. 4(b), which were calculated in the low-current limit. In a plane-parallel diode, the transit time under space-charge-limited conditions is expected to be 50% longer than under non-space-charge-limited conditions.[6] However, for our coplanar diode, the calculations show that the space-charge field is much more localized near the cathode than for the plane-parallel case, where the effect of the space-charge field is felt throughout the cathode-anode space.

We experimentally investigated the influence of space charge on the fall time of the diode by holding V_b constant and varying the UV power incident on the diode from 2 to 6 mW. The signal amplitude varied by a factor of 8, suggesting that there is a significant component of two-photon emission to the signal. Nevertheless, over this range in signal amplitude, the measured rise and fall times remained unchanged, thus confirming our expectations discussed above.

This analysis allows us to project that if the bias voltage between the strips could be increased to the 100–150 V level, the device fall time could be reduced to < 5 ps. As mentioned above, we were limited to 60 V applied bias by avalanche breakdown in the silicon between the strips. Since the silicon is only needed in the sampling gap, it should be possible to fabricate a device capable of sustaining considerably higher bias voltage by eliminating the silicon between the strips.

As shown in Fig. 3, the measured 10–90% rise times were 4–6 ps, with a weak dependence on V_b. Since the distance between the photodiode and the sampler was only ~ 1 mm, we do not expect pulse dispersion on the stripline to contribute to this time scale.[3] The photoconductive sampler was independently measured to have a 2 ps response time. We would therefore expect the limiting rise time of the measured waveform to be ~ 2 ps. Rise times longer than 2 ps would presumably be determined by flight time effects and scale as $1/\sqrt{V_b}$. However, from Fig. 3, the observed limiting rise time is ~ 4 ps. The origin of the increased rise time is not yet fully understood, but may be related to the fact that, since the electrons do not return to the anode, the excitation of the line is asymmetric. This is similar to the case of photoconductive side-gap excitation, which has been shown to yield degraded frequency response compared to the symmetric case of sliding contact excitation.[8]

In conclusion, we have demonstrated a new ultrafast radiation detector by incorporating a microfabricated vacuum photodiode into a coplanar stripline geometry. The device shows a 4 ps rise time and a 12 ps fall time. Reduction of the fall time to < 5 ps appears to be straightforward, and further improvements may be possible by optimizing the geometry. We anticipate that this device will be particularly attractive as an ultrafast detector for vacuum ultraviolet and soft x-ray radiation where photocathode materials are available with high quantum efficiency.[1]

[1] J. A. R. Samson, *Techniques of Vacuum Ultraviolet Spectroscopy* (Pied, Lincoln, Nebraska, 1967).
[2] For example, Hamamatsu Corp., Bridgewater, NJ 08807, model R1328U.
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