Subnanosecond single-photon timing with commercially available germanium photodiodes

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We demonstrate that commercially available germanium avalanche photodiodes can achieve single-photon sensitivity and subnanosecond time resolution at 77 K. Experiments show that the detector trapping phenomena give the main contribution to the detector noise. Therefore technological efforts will be welcome to overcome these limits that are due to the material quality. These devices are suitable for the detection of optical fibers with centimeter resolution at 1.3–1.5 µm. Further improvements in the timing performance can be obtained by suitable device design.

Extremely fast photodetectors, capable of single-photon sensitivity in the near-infrared wavelength range, are needed in the development of laser sources for the characterization of optical fibers. In research on semiconductor materials, and in pharmaceutical and photochemical studies. Among currently available single-photon detectors, sensitivity at 1.3 µm is attained only by photomultiplier tubes with a cooled S1 photocathode and by silicon single-photon avalanche diodes through the band-gap-narrowing effect. Though the quantum efficiency is only 10−6–10−7, the low detector noise permits measurements of diode-laser pulse shapes at 1.3 µm, but averaging over a long measure time, at least 10 min, is needed. Measurements of weaker optical signals are out of the question.

It is well known that avalanche photodiodes (APD) can reach single-photon sensitivity when operated biased below the breakdown voltage Vb (Geiger-mode operation). Single-photon counting with III–V avalanche detectors has already been demonstrated. Timing performance of germanium APD's in the nanosecond range has been reported, but this result is far from the best performance. We have demonstrated that silicon single-photon avalanche diodes can mark the arrival time of single optical photons with a resolution of 20 ps FWHM. Since the avalanche physics is similar, there is no evident reason for germanium and III–V semiconductor APD's not to reach comparable results.

As a first step in the development of high-sensitivity single-photon detectors in the near-infrared range, we investigated the performance of some commercially available germanium APD's. In this Letter we report for what is to our knowledge the first time that germanium APD's, cooled at 77 K, can reach single-photon sensitivity with time resolution well below 1 ns. Experiments clearly show that carrier trapping phenomena give the main contribution to the detector noise. Therefore technological efforts will be welcome to overcome these limits that are due to the material quality.

In order to work in the Geiger mode, an APD must have a uniform breakdown voltage Vb over the whole junction area and low dark current. Therefore we selected samples among commercially available germanium APD's having a small sensitive area and a planar structure with a diffused guard ring, which prevents edge breakdown. The results reported were obtained with Fujitsu FP1-135S1 germanium APD's with a 30-µm diameter, a primary multiplied dark current Idm lower than 5 nA, and Vb = 34 V at room temperature and, at 77 K, Vb = 23 V. Devices selected for low dark current were cooled in a cryostat and first characterized by a curve tracer. Above 100 K the thermal generation rate of carriers in the photodiode volume is so high that, as soon as the bias exceeds Vb, the avalanche is immediately triggered. Below 130 K the reverse I–V curve clearly shows a characteristic bifurcation above Vb. One of the branches corresponds to zero current flowing through the device, which means that the detector can remain quiescent as long as the bias is swept above Vb; not even a single thermally generated carrier can trigger the avalanche.

All the measurements reported in the following were performed at 77 K; the detector was operated in a gated mode with an active quenching circuit (AQC). At standby the diode was reverse biased below Vb, with one terminal connected to the dc bias source and the other to the input of the AQC. An external pulse generator triggered the AQC, which raised the bias to Vb > Vb for a time interval T on. The AQC performs the following task: (i) it sensed the onset of the APD avalanche current and provides a standard output pulse, and (ii) after ~20 ns, by means of a low-impedance driver, it swiftly lowers the APD bias voltage below Vb, thus quenching the avalanche. The APD was held off for a time T off until the external pulse generator started the procedure again.

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The performance of the selected devices was tested in a conventional time-correlated photon-counting setup. The signal from the external pulse generator was employed not only to gate the APD operation but also to trigger a laser-diode pulser, which synchronously emitted a light pulse at 1.3 μm, with a 70-ps FWHM duration. A time-to-pulse-height converter measured the time delay between the emission of the optical pulse and the detection of the photon. A histogram of the measurements was collected with a multichannel analyzer.

Figure 2 shows a measurement of the laser pulse performed with a Fajtont APD operating at 1 V above $V_c$. Since the laser pulse is much shorter than the measured pulse, the histogram directly gives a characterization of the APD timing performance. The 250-ps FWHM is remarkably better than the previously quoted nanosecond limit. The shape of the detector response clearly shows a tail. Similar tails were observed in the response of silicon devices, as a result of photogenerated carriers reaching the APD junction by diffusion. Figure 3 shows the dependence of the time resolution on the excess bias voltage.

The performance of these germanium APDs is suitable for OTDR measurements on single-mode optical fibers.
fibers working at 1.3 μm, where, at the same time, it is possible to resolve Fresnel reflections a few centimeters apart and to measure accurately the fiber Rayleigh scattering with centimeter resolution. The minimum detectable optical power, $P_0$, can be estimated from

$$P_0 = \frac{\text{NEP} \sqrt{\text{SNR}}}{\eta N \Delta t}$$

where NEP is the detector noise-equivalent power, $\eta$ is the number of laser pulse repetitions employed in the measurement, $\eta$ is the detector quantum efficiency, and $\Delta t$ is the histogram channel width. The operating bias will be decided by a trade-off between the required time resolution and sensitivity. Let us assume operation in optical time-domain reflectometry with the germanium (APD) at a 0.5-V excess bias ($\eta > 5\%$) and the gain-switched laser (30-mW peak power) described above. In order to avoid a considerable enhancement of $R$ induced by trapping, the detector should be operated in the gated mode and the laser pulse period should be longer than 200 μs. Under this condition $R = 80$ kHz, with a corresponding dark count-limited NEP = $1.2 \times 10^{-11}$ W Hz$^{-1/2}$. The 280-μs interval corresponds to the 0.95-th quantile delay of a signal backscattered from a fiber position 20 km from the fiber input. Assuming a 0.35-dB/km attenuation, we estimate the corresponding backscattered Rayleigh power reaching the detector to be 0.24 pW. If we take $\Delta t = 100$ ps, that is, a spatial resolution of 1 cm, the signal-to-noise ratio reaches unity after ~130,000 repetitions of the laser pulse, that is, after only 26 s.

In conclusion, we have demonstrated subnanosecond photon timing at 1.3 μm with a germanium APD. The device is suitable for measurements of short optical pulses in the near-infrared range and for optical time-domain reflectometry characterization of optical fibers at 1.3–1.5 μm with centimeter resolution. The device tested has not been purposely designed for Geiger-mode operation. We believe that specially designed germanium APD's can overcome the technological limitations of present devices, offering the possibility of operation with less deep cooling and with better time resolution, not far from silicon photodiode performance (20 ps FWHM).7

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References