All-Silicon Avalanche Photodiode Sensitive at 1.3 \( \mu \text{m} \) with Picosecond Time Resolution

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**Abstract**—We report the first experimental demonstration that an all-silicon photodiode can be used to measure the pulse shape of laser diodes emitting at 1.3 \( \mu \text{m} \). In order to allow the light absorption at these wavelengths, we exploit the band-gap narrowing phenomenon in heavily doped silicon. The device operates as a single photon detector in a time-correlated photon counting setup. The quantum efficiency of the detector, though only \( 10^{-7} \), together with the very low noise (\( \approx 100 \) dark pulses per second) enable easy measurements on standard diode lasers. The use of standard silicon processing and the room-temperature operation are definite advantages of the device.

TRANSIENT luminescences in semiconductor analysis, fluorescent decays from synthetic bacteria, measurements of the pulse waveform of long-wavelength laser diodes, not to mention optical fiber transmissions, require very fast photodetectors with sensitivity in the near-infrared range (NIR). Germanium and III–V compounds avalanche photodiodes (APD’s) provide high quantum efficiency in NIR and fast amplification. However, the gain is low, at best a few \( 10^3 \), and very noisy. Fast photomultiplier tubes (PMT) are available with high internal gain, at least \( 10^5 \). Beyond 900 nm, the only employable photocathode, the \( S1 \) type, features a quantum efficiency \( \eta \) that exponentially falls going to higher wavelengths: 1.3 \( \mu \text{m} \) it is \( 10^{-6} \). Furthermore, PMT’s with \( S1 \) photocathode require cooling well below 0°C.

By using PMT’s, the waveform of optical pulses in the NIR can be measured only by resorting to time-correlated photon counting [1], [2] (TCPC). Picosecond resolution has been attained [3] with ultrafast microchannel plate photomultipliers (MCP) by using this technique. Also APD’s can detect single photons at picosecond resolution by working in Geiger mode, i.e., reverse biased at a voltage higher than the breakdown. Twenty picosecond full width at half maximum (FWHM) were attained by using TCPC with silicon devices [4], [5]. With Germanium and III–V APD’s, however, Geiger mode operation has been so far obtained with only moderate time resolution [6]–[8].

There would be a tremendous interest in fabricating silicon photodiodes sensitive to the 1.3–1.5 \( \mu \text{m} \) wavelength range. If such a device were available, all-silicon optical fiber receivers could be monolithically integrated. Silicon detectors are however generally considered unemployable beyond 1.1 \( \mu \text{m} \). In fact, the absorption length of silicon steeply rises from 0.25 cm at 1.1 \( \mu \text{m} \) to 600 cm at 1.2 \( \mu \text{m} \) and to 1000 cm at 1.3 \( \mu \text{m} \) [9]. Since the width of the junction depletion layer of a photodiode must be limited to a few microns in order to obtain fast responses, (carrier transit time is 10 ps/\( \mu \text{m} \)), the typical quantum efficiency falls well below \( 10^{-6} \) already at 1.2 \( \mu \text{m} \).

In this letter, we experimentally demonstrate for the first time that special silicon APD’s fabricated with standard silicon technology show a residual sensitivity in the 1.3 \( \mu \text{m} \) wavelength range. The quantum efficiency is smaller than that of PMT’s with photocathodes, but this sensitivity is enough to make it possible to use these detectors in some of the aforementioned experiments.

In principle, the absorption efficiency at the long-wavelength edge of a semiconductor may be enhanced by altering the material structure in such a way as to reduce the bandgap. Our approach was to exploit the band-gap narrowing (BGN) induced by high concentration of dopants in silicon, a widely studied and debated phenomenon [10]–[16]. BGN is important in regions doped more than about \( 10^{19} \text{ cm}^{-3} \). The presence of dopants can effectively reduce the bandgap of silicon by 150 meV and more. It is thus possible, at least in principle, to reduce the gap to less than 1 eV, thereby allowing the detection of photons of 1.3 \( \mu \text{m} \) wavelength by employing detectors fabricated with standard silicon technology.

The experiments were performed with devices whose structure is shown in Fig. 1. The absorption of photons takes place in the top neutral n⁺ layer obtained by phosphorus diffusion. The photogenerated carriers travel to the edge of the p–n junction, which is biased above the breakdown voltage. The first carrier reaching the junction initiates a macroscopic avalanche process. Consequently, the current through the junction steeply rises to an easily detectable level. The rising edge of this current waveform is synchronous with the arrival time of the photogenerated carrier.

The high concentration gradient of the phosphorus dopants, causes an electric field in this quasi-neutral region that pushes the photogenerated minority carriers towards the depleted region. This is similar to what happens in the base of diffused bipolar transistors. In the present struc-

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ture this field is greater than 2 kV/cm everywhere. The resulting drift velocity is never less than 2.5 \times 10^5 \text{ cm/s}, and the transit time is \approx 40 \text{ ps}. It should however be noted that diffusion mechanisms also take place in this region. This phenomenon results in a reduction of the average transit time to \approx 20 \text{ ps}, but also in a statistical spread of the individual arrival times at the edge of the junction.

The present device is therefore conceptually similar to the separate absorption, grading, and multiplication SAGM photodiode. In fact, absorption and multiplication occur in spatially different regions; moreover, there is no abrupt change of band gap between the two regions since the n^- region is obtained by diffusion (see Fig. 1). This point is important since an abrupt change in the bandgap causes charge trapping phenomena at the interface, and in turn a reduction in the device speed. The thickness \( W \) of the absorption layer has to be designed with care, since it sets both the speed of response and the sensitivity of the detector. In this regard, it should be noted that the minority carrier lifetime in a heavily doped region is small, so that an excessive increase of the absorption region is of no help for increasing the quantum efficiency, but only slows down the detector. In our devices \( W = 0.3 \ \mu \text{m} \), and the average transit time is \approx 20 \text{ ps}, as already mentioned: this is much lower than the estimated minority carrier lifetime in the neutral region. As far as the quantum efficiency is concerned, the probability that a photogenerated carrier will reach the avalanching region by diffusion is \( p_d \approx 0.5 \), if recombination is assumed to be negligible in the n^- region. In operating conditions, a triggering probability \( p_t \) of 0.4 was estimated, based on the method described by Oldham and Antognetti [17]. In order to obtain the quantum efficiency, the knowledge of the absorption probability \( p_a \) is also required. The value of \( p_a \) is dependent on the effectiveness in the reduction of the bandgap.

Unfortunately, the values of the band-gap shrinkage are not known with enough accuracy for wavelengths in the region of 1.3 \mu m [11]. Based on Pankove's formula [18], experimental data obtained by Wagner [14] were extrapolated to the 1.3 \mu m wavelength. By considering only the first 100 nm of the n^- absorption region, which are the most heavily doped, one gets \( p_a \approx 5 \times 10^{-7} \). The quantum efficiency \( \eta = p_e p_d p_t \) was thus estimated \( \eta \approx 10^{-7} \) for the detector in working conditions. In obtaining this estimate, we neglected free-carrier absorption, which is the main absorption mechanism in silicon in this wavelength range. This is reasonable, since 1) photons absorbed through this mechanism do not generate minority carriers, and thus cannot be detected and 2) the number of absorbed photons in the first 100 nm of silicon is very low, of the order of \( 10^{-2} \), and thus the photon flux at any depth in the absorption region can be considered essentially constant.

The experiments were performed with a gain-switched laser diode having the emission peak at 1.3 \mu m. The apparatus was a standard time-correlated photon counting setup [1]. Fig. 2 shows the optical pulse shape of the laser as detected with our device. No attempt was made to focus the laser on the 10 \mu m diameter area of the device. An interference filter was interposed, to attenuate lower-wavelength wings in the laser spectrum. The measure was averaged on \approx 5 \cdot 10^3 laser pulses. The manufacturers measured the laser pulselength in 60 ps full width at half maximum by using an ultrafast III-V photodiode. The duration of the laser pulse as detected with the device is 70 ps. We conclude that the device contributes 40 ps to the observed curve. From the knowledge of the optical pulse energy, we obtained a quantum efficiency of the device of \( \eta \approx 10^{-7} \).

A proof that the absorption of 1.3 mm photons takes place mostly in the heavily doped n^- region was obtained by comparing the present curve with that obtained with a 904 nm laser diode and the same detector (see Fig. 3). With the 904 nm laser, a long tailing of the wave shape is observable, due to photogenerated carriers in the neutral p region which slowly reach the high field region by diffusion. Such a tail is completely absent with the 1.3 \mu m laser, as shown in Fig. 3. A further proof that the absorption takes place in the heavily doped n^- layer can be obtained by considering the fall of the light curve in logarithmic scale. The observed tail is well fitted by an exponential with time constant 24 ps, as shown in Fig. 4. On the other hand, the rising edge of the curve can be fitted with an exponential having 13 ps time constant. By quadratic deconvolution a time constant of 20 ps is obtained. This value of \( \tau \) is slightly lower than the value (24 ps) predicted by solving the time-dependent diffusion equation in the top neutral layer without taking into account the electric field. Since the electric field effect is to reduce the transit time, we concluded that the asymmetry in the shape of the optical pulse is consistent with the assumption that photon absorption takes place only in the top layer.

Another mechanism that could result in absorption of photons in the 1.3 \mu m wavelength range is the photon-assisted tunnelling in the high field region of the device.
This phenomenon is extremely sensitive to the value of the peak electric field, and thus to the applied voltage. However, we did not observe any significant variation of the quantum efficiency with the bias voltage that could not be ascribed to the variation of the triggering probability $p_i$. We concluded that photon assisted tunnelling does not contribute appreciably to the observed sensitivity of the detector.

In conclusion, we have shown for the first time that an all-silicon photodiode can be used to measure the pulse shape of laser diodes emitting at 1.3 μm. The device operates as a single photon detector in a time-correlated photon counting setup. A clean shape of the pulse is obtained, which is free of risings and undershoots; the technique thus allows measurements of the pulse shape over many decades of the light intensity as we have already pointed out elsewhere [20]. The quantum efficiency of the detector, though only $10^{-7}$, together with the very low noise (=100 dark pulses per second) enable easy measurements on standard diode lasers. The use of standard silicon processing and the room-temperature operation are definite advantages over photomultiplier tubes.

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