Enhancement of the infrared detection efficiency of silicon photon-counting avalanche photodiodes by use of silicon germanium absorbing layers

Alison Y. Loudon, Philip A. Hiskett, and Gerald S. Buller

Department of Physics, Heriot-Watt University, Edinburgh EH14 4AS, UK

Roger T. Carline, Dave C. Herbert, W. Y. Leong, and John G. Rarity

QinetiQ, St. Andrews Road, Malvern, Worchestershire WR14 3PS, UK

Received September 13, 2001

An enhancement of the infrared detection efficiency of Si photon-counting detectors by inclusion of SiGe absorbing layers has been demonstrated for what is believed to be the first time. An improvement of 30 times in detection efficiency at a wavelength of 1210 nm compared with that of an all-Si structure operated under identical conditions has been measured. The $Si/Si_{0.7}Ge_{0.3}$ device is capable of room-temperature operation and has a response time of less than 300 ps. © 2002 Optical Society of America

OCIS codes: 040.0040, 040.5160, 040.6040, 040.3060.

Quantum key distribution,[1] time-resolved photoluminescence,[2] and photon-counting time-of-flight ranging[3] are three rapidly expanding application areas that depend on the detection of single photons at wavelengths from 400 to 1600 nm. During the past decade, single-photon avalanche diodes (SPADs) have become commonplace in these types of application. SPADs, in particular,[4,5] have been used to great effect at wavelengths below 1 μm because of their high efficiency, low dark-count rates, high-speed response, and near-room-temperature operation. Unfortunately, because of their absorption wavelength cutoff at approximately 1.1 μm and subsequent low detection efficiency beyond this wavelength, Si SPADs are not suitable for the numerous infrared applications. In Ref. 6, for example, the detection efficiency of a Si device at 1.3 μm was measured as $\sim 10^{-5}\%$. Reported here is what we believe to be the first attempt to enhance the detection efficiency of Si avalanche structures beyond 1.1 μm by use of SiGe absorbing layers.

A SPAD is an avalanche photodiode that, when it is reverse biased above its breakdown voltage, can produce a macroscopic current pulse following the absorption of a single photon. Avalanche photodiodes (i.e., non-photon-counting devices) were fabricated previously[7] by use of $Si/Si_{1-x}Ge_x$ multiple-quantum-well (MQW) material in which the absorption occurs in $Si_{1-x}Ge_x$ alloy layers and the multiplication occurs in a separate Si layer. This separate absorption multiplication device structure is more commonly used in III–V devices, e.g., InGaAs/InP avalanche photodiodes.[8] The same concept was employed in the design of a $Si/Si_{1-x}Ge_x$ SPAD for this research (see Fig. 1).

A photon absorbed in the SiGe alloy layer creates an electron–hole pair. The device is designed in such a way that the electron then drifts under the applied electric field into the higher-field Si multiplication layer. The carrier is accelerated in the high field and rapidly gains sufficient kinetic energy to initiate an avalanche via impact ionization. When the bias that is applied is above the diode's breakdown voltage, as in photon-counting operation, the electric field is high enough that the avalanche may become self-sustaining.

The absorption wavelength is highly dependent on the Ge concentration in the alloy layers. Theory suggests that absorption at 1.55 μm can be achieved with >85% Ge.[9] Because of the lattice mismatch between Si and SiGe, however, the resulting strain limits the width of a defect-free alloy layer to a critical thickness (dependent on Ge concentration and growth temperature).[7] The strain, though, narrows the bandgap further, so using MQWs both increases the total alloy thickness and extends the absorption wavelength, improving the probability of infrared photon detection.

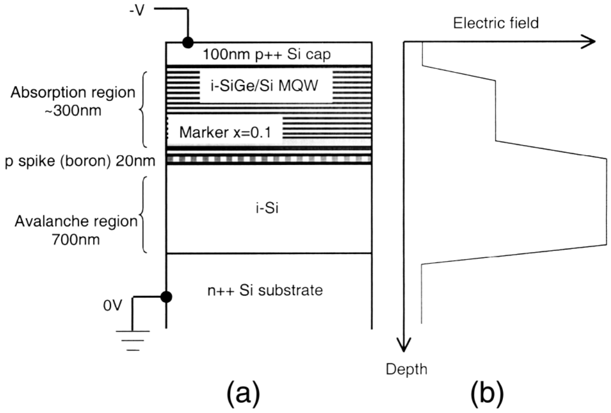

Fig. 1. Device structure, showing separate absorption and multiplication layers. The absorption layer in the Si control device is made up of intrinsic silicon (i-Si) only, with no MQWs. (b) Schematic of the electric field profile through the device.

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The devices discussed here consist of an all-Si control sample and a sample incorporating a $Si/Si_{1-x}Ge_x$ MQW region with ~30% Ge concentration, as shown in Fig. 1. An n^{++} Si substrate was used, and an intrinsic Si multiplication region grown to a thickness of 700 nm on top. Twenty-five repeats of a Si spacer layer (varying from 7.1 to 5.7 nm wide) and a 3.5-nm $Si_{0.7}Ge_{0.3}$ well were then grown, and a 100-nm Si p^{++} cap layer was added. The all-Si sample was identical except for the absorption region, which consisted only of Si and no MQWs. The Ge $x = 0.1$ marker layer was used as an etch stop in the fabrication process, and we added a p-type doping spike to create the high-field region in the avalanche layer. These wafers were processed into 120-μm-diameter circular mesa devices.

Initial photoresponse tests suggested a maximum absorption wavelength in the Si control sample of ~1.1 μm and a 1.2-μm maximum in the $Si/Si_{0.7}Ge_{0.3}$. We therefore attempted photon-counting detection efficiency measurements at both 826 and 1210 nm on both samples to determine whether the addition of the alloy layers improved the efficiency beyond 1.1 μm.

The measurement technique used is described in detail by Hiskett *et al.*[10] The 826- or the 1210-nm laser was gain switched to produce an optical pulse of duration ~200 ps at a repetition frequency of ~10 kHz. Neutral-density filters were used to attenuate the pulses to a level at which there was a negligible probability that the devices would detect more than one photon per pulse.

A self-sustaining avalanche must be quenched so that the device is protected and so that it will detect the next photon. Gated mode operation[11] was chosen as the most suitable quenching method in this case. A constant 3-V high ac gate pulse was applied in conjunction with a variable dc bias level, which was always kept below breakdown. This gate pulse brought the device to the required voltage above breakdown (excess bias) in synchronization with the arrival time of the photon. The high contact resistance, and hence the large RC time constant, that was found to exist in these devices, however, caused large transients on the output signal. This is a common effect often seen in gated mode operation.[12] A 65-ns-long rise time was required for reduction of the transient at the start of the gate pulse to below the magnitude of the avalanche pulse so that the avalanches could be discriminated and recorded. A 100-ns-long gate pulse was therefore used so that the device would be at full excess bias for ~30 ns before the removal of the ac pulse switched the device off, quenching any avalanche.

The results of measurements taken with the devices cooled to 200 K are shown in Fig. 2. The detection efficiency is the ratio of the number of recorded photocounts per second to the number of incident photons per second (the latter being determined from the measured power, the attenuation used, and the energy of a single photon) and is plotted versus excess bias. Although the Si control has higher detection efficiency at 826 nm, the performance is reversed at 1210 nm, at which the SiGe sample shows an improvement of 30 times over that of the Si. Additionally, the detection efficiency increases with excess bias. This is because, as the field across the devices increases, carriers generated by the incident photons are more likely to reach the multiplication region, be accelerated, ionize, and create a self-sustaining avalanche. The detection efficiency levels off in the case of the Si device when the dark-count (noise) level approaches saturation.

Measurements of the Si device could not be performed at any higher temperatures because of the dark-count saturation A temperature sweep of detection efficiency at constant relative excess bias was performed for the $Si/Si_{0.7}Ge_{0.3}$ device, however, and the results are shown in Fig. 3. The detection efficiency increases significantly with temperature. Using a constant relative excess bias ensured that the probability of a carrier's triggering an avalanche once inside the multiplication layer remained constant.[10] The rise in detection efficiency must therefore be due to two things: (1) as the bandgap shifts, the probability of photon absorption at 1210 nm increases, and (2) the increase in the absolute field required for avalanche breakdown increases the probability of a carrier's drifting into the high-field multiplication layer.

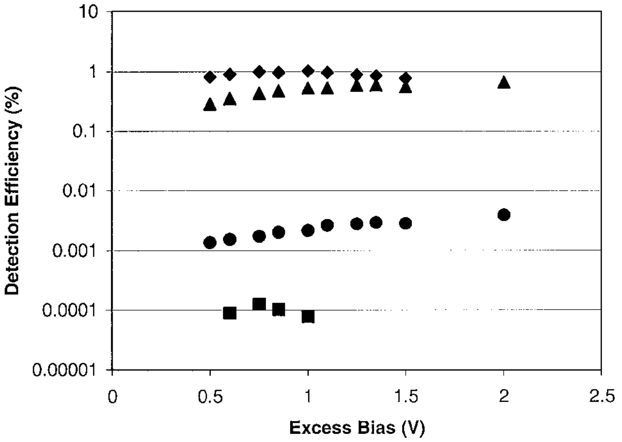

Fig. 2. Detection efficiency at 200 K of both the Si control at 826-nm (◆) and 1210-nm (■) wavelengths and the SiGe device at 826-nm (▲) and 1210-nm (●) wavelengths plotted versus excess bias.

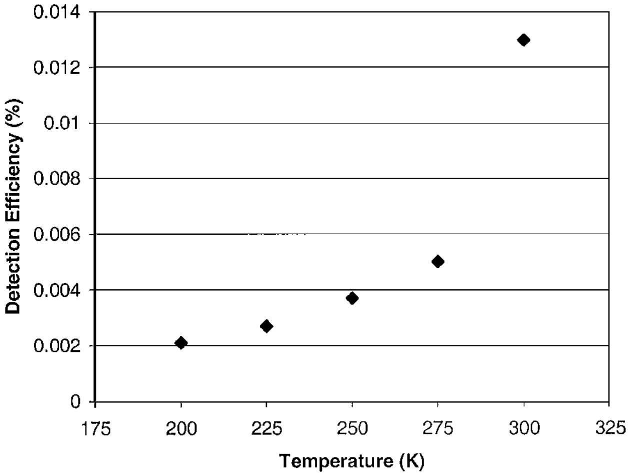

Fig. 3. Detection efficiency of the SiGe device at a wavelength of 1210 nm and 3.6% excess bias (equivalent to 1-V excess bias at 200 K) plotted versus temperature.

The dark-count rate in the Si device (normalized to 1 s) is $\sim 1 \times 10^7$ counts per second (cps) at 200 K, much higher than that of the SiGe device, which is $\sim 1 \times 10^5$ cps at 200 K and approaches 1×10^7 cps only at room temperature. The noise equivalent power of the Si device at 1210 nm is therefore 1×10^{-11} W Hz$^{-1/2}$, higher than that of the SiGe device, which has a noise equivalent power of $\sim 5 \times 10^{-12}$ W Hz$^{-1/2}$ at all measured temperatures. At 1-V excess bias, the FWHM response of the SiGe device, measured as the time jitter between the laser trigger and the detected rise edge of the photopulse, is just under 300 ps.

In conclusion, a SPAD containing a Si/$Si_{0.7}Ge_{0.3}$ MQW absorbing region has been demonstrated for what is to our knowledge the first time. An improvement in detection efficiency of ~30 has been measured at 1210 nm over an all-Si control sample operated under identical conditions. Even with a large 120-μm-diameter device, room-temperature operation was achieved with a response time of ~300 ps. Although the actual detection efficiency is modest and the noise high in comparison with those of commercial Si devices[4] and developmental thin-junction Si SPADs,[5,6] the enhancement of infrared counting performance demonstrated here illustrates potential benefits of the inclusion of SiGe layers. There is reason to believe that, with an improvement in device fabrication and the use of higher-Ge-concentration alloy layers and possible waveguide-absorbing structures,[13] the device performance could be further improved.

This work was carried out as part of Technology Group (7) of the UK Ministry of Defence Corporate Research Programme and with the support of the UK Engineering and Physical Sciences Research Council (GR/L8195). A. Y. Loudon's e-mail address is a.y.loudon@hw.ac.uk.

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