Resonant-Cavity-Enhanced Single Photon Avalanche Diodes

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We present a resonant-cavity-enhanced Single Photon Avalanche Diode (SPAD) fabricated on a reflecting silicon-on-insulator (SOI) substrate. The substrate incorporates a two period distributed Bragg reflector fabricated using a commercially available double-SOI process. The resonant-cavity-enhanced (RCE) SPAD detectors have peak photon detection efficiencies ranging from 41% at 780nm to 32% at 850nm and time resolution of 35ps full-width at half maximum. Typical dark count rates of 500, 5000 and 100000 c/s were measured at room temperature with RCE SPADs having respectively 8, 20 and 50µm diameter.

Fluorescence spectroscopy is nowadays widely used as analytical and research tool in several fields, such as chemistry, biology and materials science (see [1] for review). Miniaturized detectors with single-photon sensitivity are required in these applications to face the steady trend toward smaller sample volumes, lower excitation intensity and compact, low-cost analytical systems. Planar Single Photon Avalanche Diodes (SPADs) fabricated on double epitaxial silicon substrates offer the typical advantages of solid state devices (miniaturization, ruggedness, low voltage, low power, low cost, etc.) along with remarkably good photon timing resolution (< 35ps full width at half time) and high photon detection efficiency (PDE) in the visible range (~ 50% at 550nm) [2]. A shortcoming of planar SPADs is the relatively low PDE in the near infrared (NIR) range from 700 to 850nm (values from 25% to 12% are typical). Although this performance is much better than that of photomultiplier tubes, there is a general request for higher PDE in the NIR range fueled by the increasing use of long-wavelength fluorescent labels and probes. The shift toward NIR fluorophores is of current interest for several reasons. The autofluorescence of biological samples like cells and tissue decreases with increasing wavelength, thus improving the sensitivity of fluorescence detection. In addition, light of longer wavelength penetrates tissue more easily due to the reduced scattering, making longer wavelength excitation and detection more attractive for in-vivo molecular imaging.

A higher PDE can be achieved by increasing the thickness of the depletion region. However, this approach leads to higher operating voltage (hence higher power dissipation) and reduced timing resolution [3]. Alternatively, a Fabry-Perot cavity can be exploited to enhance the optical field inside the SPAD detector at resonant wavelengths. Such a resonant cavity can be formed using a buried reflector and the air/semiconductor top interface [4]. This approach enables higher PDE with the same thickness of the depletion region, thus avoiding adverse effects on photon timing resolution and power dissipation.

We fabricated resonant-cavity-enhanced (RCE) SPAD devices on a reflecting silicon-on-insulator (SOI) substrate having an epitaxy ready single crystalline surface. The substrate incorporates a two period distributed Bragg reflector (DBR) fabricated using a commercially available double-SOI process [5]. The double-SOI wafers were specifically tuned to achieve a reflectance in excess of 90% around 850nm. Starting from these wafers, double epitaxial SPADs with active area diameter of 8, 20 and 50µm were fabricated using the process described in [6]. Preliminary prototypes were coated with a single, 100nm thick SiO_2 layer to prevent reliability problems. A slight reduction of the cavity finesse at 850nm is therefore expected due to the lower surface reflectivity. Fig. 1 shows the cross section of the fabricated devices. SPADs were tested at room temperature with an excess bias voltage of 5V. “Control” SPAD devices made on conventional substrates were fabricated in the same batch for comparison purposes.

Dark count rate (DCR) was measured by operating SPAD devices with an external active quenching circuit (AQC). A hold-off time of 300ns was enforced by the AQC, such that afterpulsing effects are reduced to a negligible level. The typical DCR is 500, 5000 and 100000 c/s for SPADs having respectively 8, 20 and 50µm active area diameter. The DCR of control SPADs is about one order of magnitude lower, showing that the defectivity of double-SOI substrates is higher. Fig. 2 shows the PDE of both RCE and control SPAD detectors as a function of wavelength. As expected, no substantial difference is observable up to 650nm, since either most of the incident photons are absorbed before reaching the buried mirror or the buried mirror itself has a low reflectivity [5]. Conversely, a remarkable improvement of the PDE is observable between 750 and 950nm. Peak PDEs ranging from 41% at 780nm to 32% at 850nm were observed. Resonance peaks appear undersampled due to the rough wavelength step (5nm) used in the measurement. It must be pointed out that

most of the fluorophores used in fluorescence spectroscopy measurements exhibit a rather broad emission spectrum (FWHM ~ 50nm) compared to the width of the resonance peaks. Therefore, the *effective* PDE of the SPAD device is given by the weighted local average of the *actual* PDE. In the next generation of devices, resonance peaks will be almost completely smoothed by replacing the top oxide layer with a suitable antireflection (AR) coating. The additional AR coating will result in a “two-pass” detector where the light enters the photodetector and reflects off the buried mirror, thus doubling the effective absorption width.
Fig. 3 illustrates the time response of RCE and control SPAD devices to an ultrafast laser diode (15ps FWHM, 820nm wavelength), measured in a Time Correlated Photon Counting set-up. In both cases, the time resolution FWHM is about 35ps, while the diffusion tail of the RCE SPAD is remarkably longer. Photogenerated electrons scattered at the buried silicon-oxide interface and redirected back in the epitaxial layer provide a partial explanation of the longer tail. Further investigations are ongoing to better clarify this point.

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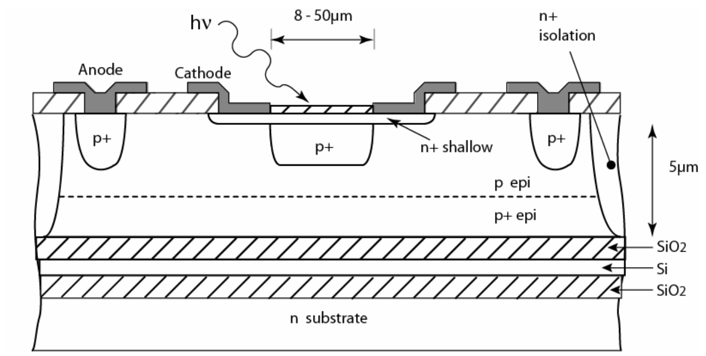

Fig. 1 Cross section of the RCE-SPAD structure.

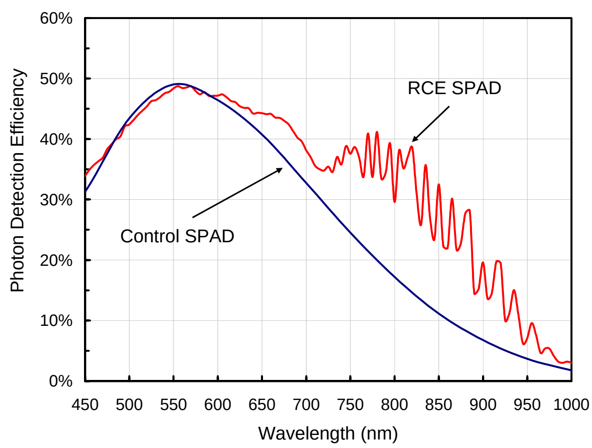

Fig. 2 Photon detection efficiency of RCE and control SPAD detectors at 5V excess bias voltage.

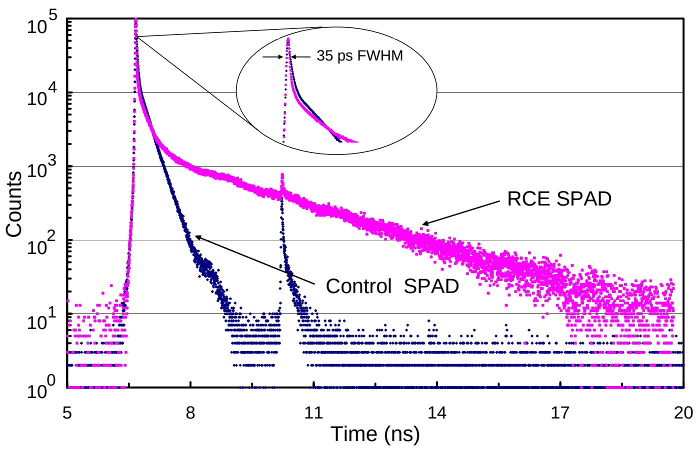

Fig. 3 Time response of RCE and control SPAD detectors to a picosecond laser pulse at 820nm (the small secondary peak occurring at ~10ns is due to a reflection at the fiber connector). Both SPADs have an active area diameter of 50μm and are operated at 5V excess bias voltage.