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Back-illuminated silicon resonant cavity-enhanced photodetector at 1550 nm

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ABSTRACT

In this paper a novel photodetector at 1550 nm, working at room temperature and completely silicon compatible, is reported. The detector is a resonant cavity-enhanced structure incorporating a Schottky diode back-illuminated and its working principle is based on the internal photoemission effect. The device performances in terms of responsivity are numerically calculated for different values of bottom reflectivity. Finally, a preliminary device was realized and characterized in order to validate the theoretical results.

1. Introduction

Silicon (Si) photodetectors (PDs) have already found wide acceptance for visible light (400–700 nm) applications [1], while for applications in optical communications in the near-infrared (IR) wavelength range between 800 and 900 nm they suffer from low bandwidth efficiency products due to the long absorption length necessitated by the small absorption coefficient. In Si, considering the inter-band transition, a cutoff wavelength of about 1100 nm is obtained; therefore, in order to obtain PD working at the 1300–1550 nm fiber optic communication wavelength range, we have two possible options. The first is to use a semiconductor that is sensitive around the 1300–1550 nm wavelength range. Germanium (Ge) is a good candidate [2–5], given its smaller direct energy band gap of 0.8 eV, but unfortunately bulk Ge is still a relatively weak absorbing material at 1550 nm. As a result, a thick Ge-active region would be required to obtain a certain level of quantum efficiency, resulting in a slow device. Besides, the growth of this compound on Si is still a challenge in terms of cost and complexity [6]. The second option is the exploitation of the internal photoemission effect over the metal–semiconductor Schottky barrier [7]. Si- IR photodiodes based on the internal photoemission effect are not novel; in fact PtSi/p-Si junctions are usually used in the infrared imaging systems [8]. The main advantages of these devices reside in their extremely high switching speed and in their simple fabrication process, but due to the leakage photon flux within the metallic layer, their quantum efficiency is small. In order to avoid high dark current density, because of their low potential barrier (0.25 eV), these devices have to work at cryogenic temperature (70 K).

A Si-based PD working at 1550 nm is of great importance not only for fiber communication but also for optical interconnect for inter- and intra-chip communication. It is worth noting that the internal photoemission effect could allow the direct monolithic integration of PDs in a chip, which is the best option in order to integrate receivers with electronics. Starting from these reasons, in this paper, with the aim to take advantage of the internal photoemission effect, a new kind of resonant-cavity-enhanced (RCE) PD is investigated. We note that while the resonant microcavity used to enhance the photon absorption is not a new concept in PDs design, on the contrary, it is quite new to incorporate into an RCE structure, a PD based on internal photoemission effect.

In the RCE-PDs, the enhancement of quantum efficiency η is obtained by placing the active layer inside a Fabry–Perot cavity. The optical field enhancement due to the cavity allows the use of thin absorbing layers, which minimize the carrier's transit time without hampering the quantum efficiency [9]. RCE-PDs have been successfully demonstrated for a range of operating wavelengths, including Si-based detectors optimized for 850 nm [10] and Ge-based detectors designed for operation around 1550 nm [11].

In this paper, the design of a back-illuminated RCE metal Schottky barrier Cu/p-Si PD, based on internal photoemission effect at 1550 nm and working at room temperature, is proposed. A theoretical and numerical analysis of a similar structure, but

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top-illuminated, was provided by the same authors in Ref. [12]. In the top-illuminated structure, the crucial point is the realization of a metal thin film (semi-transparent). The precise control of metal thickness in nanometer (about 10 nm) and an acceptably low defect concentrations are not trivial tasks. For this reason, a novel back-illuminated device was proposed and its performances in terms of responsivity were numerically calculated for different values of bottom reflectivity. Finally, a preliminary device was realized and characterized in order to validate the theoretical results.

2. Proposed device and theoretical investigation

The sketch of the device is shown in Fig. 1. The device proposed is based on the internal photoemission effect over a Cu–Si Schottky junction introduced into a Fabry–Perot Si structure in which the cavity top mirror is the copper metal and the cavity bottom mirror is a distributed Bragg reflector (DBR), composed of quarter-wave stacks of amorphous hydrogenated Si (a-Si:H) and silicon nitride (Si_3N_4), respectively.

We point out that our structure is different from the RCE Schottky PDs in which the Schottky contact is only an electric contact and not the active layer, whereas in our device the metal layer works as the top contact and as the active (absorbing) layer at the same time. This is the crucial difference and the novelty of our proposed device.

The responsivity of a PD based on the internal photoemission effect is given by the formula [13]

$$\mathrm{Re\,sp} = \frac{\lambda\,[\mathrm{nm}]}{1242}\eta = \frac{\lambda\,[\mathrm{nm}]}{1242}A_T F_e P_E \eta_c \qquad (1)$$

where η is the device quantum efficiency, A_T is the total optical absorbance of the metal calculated by a transfer matrix method (TMM) [14], F_e is the fraction of the absorbed photon that produces photoelectrons with appropriate energy to contribute to the photocurrent [15], P_E is the total accumulated probability that one of these photoexcited electrons will be able to overcome the Schottky barrier after scattering with cold electrons and with boundary surface [16] and η_c is the barrier collection efficiency, which is bias dependent due to the image force effect [17]. The cavity effect is taken into account just in the calculation of the A_T factor.

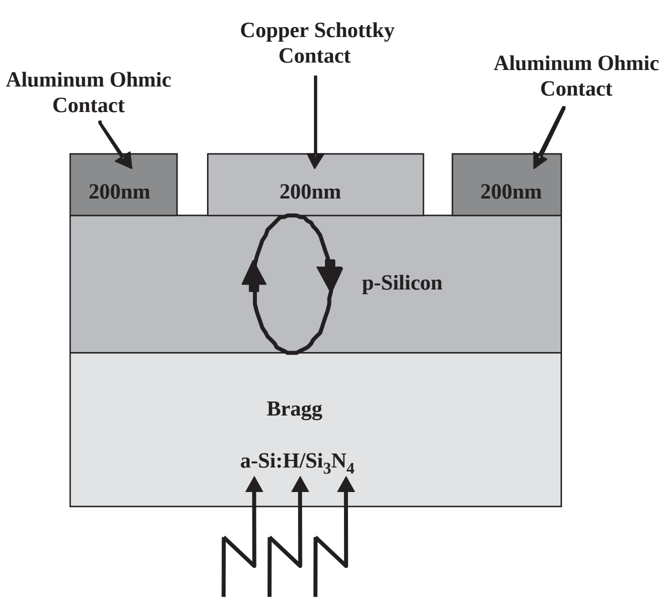

Fig. 1. Schematic cross-section of the proposed RCE Schottky photodetector.

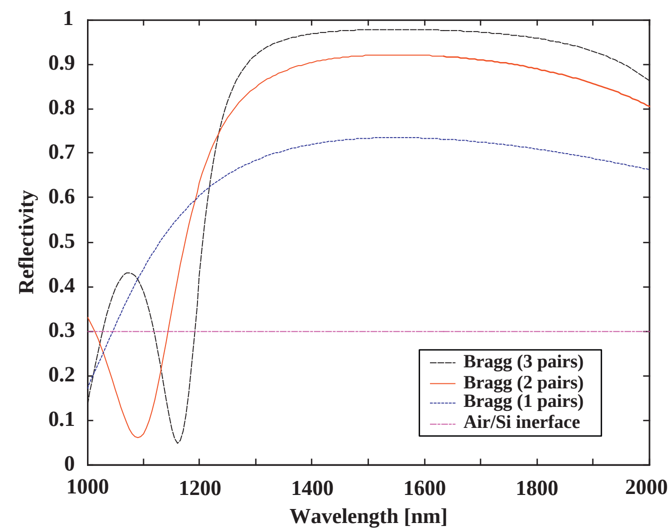

Fig. 2. Simulated device bottom reflectivity versus wavelength using a Bragg mirror formed by 3 pairs (dashed), 2 pairs (solid) and 1 pair (dotted) of a-Si:H/Si_3N_4. The dash–dot line is due to a simple air/Si interface.

By Eq. (1), devices having different bottom mirror reflectivities were numerically investigated in four cases: absence of Bragg and Bragg formed by 1, 2 and 3 pairs of a-Si:H/Si_3N_4, respectively. In Fig. 2, bottom mirror reflectivity of the proposed a-Si:H/Si_3N_4 Bragg reflector versus wavelength is reported. The curves parametrized in the function of the number of periods show that high-reflectivity and wide spectral stop band can be obtained with few periods of a-Si:H/Si_3N_4. In Fig. 3, responsivity versus wavelength at different bottom mirror reflectivities is reported.

All parameters used in our simulations are reported in Table 1 [18–22].

The results of our simulation are summarized in Table 2.

It is worth noting that a responsivity enhancement of more than an order magnitude is achieved by using a resonant cavity structure at higher finesse. The maximum responsivity of 25 μA/W obtained in our simulations is about two orders of magnitude lower compared to the top-illuminated structure numerically investigated from the same authors in Ref. [12]. We point out that this is not due to the top or back illumination; in fact, in Ref. [12] the proposed device was optimized in order to get the highest responsivity while in this work the layers' thicknesses are chosen taking into account our capability to realize a preliminary device.

Even if achievable responsivity is low, these results are encouraging in order to investigate more complex structures having a higher finesse that could provide a significant improvement of responsivity (i.e. disk or ring resonator).

3. Device fabrication and characterization

In order to validate the numerical results, we realized the simplest device previously numerically investigated. The preliminary device has a copper metal as the top mirror while the interface air/Si represents the bottom mirror.

The sample was fabricated starting from a Si substrate of 100 μm p-type slightly doped ($10^{14}\,cm^{-3}$). The collection contact and the Schottky contact were both realised on top of the Si wafer. The collection contact was realized by a 200-nm-thick aluminium thermally evaporated, patterned by a lift-off process and annealed at 475 °C for 30 min [23]. Finally, the Schottky contact was obtained, by a 200-nm-thick copper thermally evaporated and patterned by lift-off. The collection contact and the Schottky