Au, Ag and Cu-Silicon RCE photodetectors based on the internal photoemission effect at 1.55 micron

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ABSTRACT
In this paper, the design of a novel photodetector, working at 1.55µm and completely silicon compatible, is reported. The device is a resonant cavity enhanced (RCE) structure incorporating a silicon photodetector based on the internal photoemission effect. In order to quantify the performance of photodetector, quantum efficiency including the image force effect as a function of bias voltage are analytically calculated. Moreover we propose a comparison among three different Schottky barrier Silicon photodetectors, having as metal layers gold, silver or copper, respectively.

Categories and Subject Descriptors
D.4.8: Performance – *modeling and prediction, simulation.*

General Terms
Performance, Design, Theory.

Keywords
Fabry-Perot, Internal photoemission, Photodetectors, Resonant cavity enhanced, Silicon.

1. INTRODUCTION
Silicon photodetectors have already found wide acceptance for visible light (0.400-0.700 micron) applications [1], while for applications in optical communications in the near-IR wavelength range between 800–900 nm they suffer from low bandwidth-efficiency products due to the long absorption length necessitated by the small absorption coefficient. In silicon (Si), considering the interband transition, a cut off wavelength of about 1.1 micron is obtained, therefore, in order to obtain photodetector working at 1.3-1.55 micron fiber optic communication wavelength range, we have two possible option. The first is to use a semiconductor which is sensitive around the 1300–1550-nm wavelength range. Germanium (Ge) is a good candidate, 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 silicon is still a challenge in terms of cost and complexity [2]. Therefore the direct monolithic integration of photodetectors in a chip should be a more attractive solution to integrate receivers with electronics. The second option is the exploitation of the internal photoemission effect over the metal-semiconductor Schottky barrier [3]. Silicon infrared photodiodes based on the internal photoemission effect are not novel, in fact PtSi/p-Si junctions are used in the infrared imaging systems [4]. The main advantages of these devices resides 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 works at cryogenic temperature (70K). At room temperature, in order to get low dark current, devices having potential barrier height close to photon energy have to be used, but, unfortunately, their quantum efficiency is low.
Being a Si based PD having a reasonable responsivity at 1550 nm of great importance not only to fiber communication but also for optical interconnect for inter- and intra- chip communication, with the aim to try to overcome the previous limitation, in this paper, we investigate a new kind of Resonant-cavity-enhanced (RCE) photodetector based on internal photoemission effect. While the resonant cavity used to enhance the photon absorption is not a new concept in photodetector design, on the contrary, it is quite new to incorporate into RCE structure a photodetector based on internal photoemission effect.

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In Resonant-cavity-enhanced photodetectors (RCE-PD) the enhancement of quantum efficiency η is obtained by placing the active layer inside a Fabry-Perot cavity. The optical field enhancement in the cavity allows the use of thin absorbing layers, which minimizes the transit time of the photogenerated carriers without hampering the quantum efficiency [5]. RCE-PD have been successfully demonstrated for a range of operating wavelengths, including Si-based detectors optimized for 850 nm [6] and Ge-based detectors designed for operation around 1550 nm [7].

In our previous paper[8], the design of a Si Schottky Resonant-cavity-enhanced photodetectors (RCE-PD) operating at 1.55 micron, based on the internal photoemission effect, was proposed. In this paper taking advantage to the previous results, the authors gives some guidelines for the best design of the device and propose a comparison among three different photodetectors, having as Schottky metal: gold, silver or copper respectively. The photodetectors could work at room temperature and their fabrication is completely compatible with standard silicon technology.

2. DESIGN AND QUANTUM EFFICIENCY OF DEVICES

The sketch of device is shown in Fig. 1. The device proposed is based on the internal photoemission effect over a Schottky junction metal-Si, top illuminated and operating at 1.55 micron. The resonant cavity is a Fabry-Perot vertical-to-the-surface structure. It is formed by a buried reflector, a mirror top interface and in between a λ/2-silicon-layer. The buried reflector is a Bragg mirror formed by alternating layers of Si-SiO_2 structures. Deposited on λ/2-silicon-layer is a semitransparent Schottky metal and a dielectric coating layer, working as the top reflector of the resonant cavity. We point out that our structure is different from the RCE Schottky PD's in which the Schottky contact is only an electric contact and not the active layer, whereas in our device the metal layer works as top contact and as active (absorbing) layer at the same time.

The Distributed Bragg Reflector (DBR) could be formed by alternate layers of Si and SiO_2 having refractive index 3.45 and 1.45, made with an iterated Silicon-on-insulator (SOI) technique[9].

One of the many benefits of silicon is the large index contrast provided by Si-SiO_2 structures, allowing the realization of high-reflectivity, wide spectral stop-band DBR made of few periods [9]. Limitations in fabrication process usually do not allow for layer thickness as thin as (λ/4n), for this reason (3λ/4n) layers for Si were used [9]. Starting from these results, in our design we propose a DBR centered at 1.55μm formed by 4 periods of Si/SiO_2 having thickness of 340 nm and 270 nm, respectively. In order to get ohmic contact, the top layer of the DBR is supposed to be realized by a very thin but heavily doped $10^{19}cm^{-3}$ silicon layer. Regarding the top reflector of the resonant cavity, we consider three metals: gold, silver and copper, whose optical and electrical properties are summarized in table 1 [10]-[13].

The quantum efficiency of a photodetector based on internal photoemission effect, is given by the formula[10]:

$$\eta = F_e P_E \eta_c A_T \quad (1)$$

where F_e is the fraction of absorbed photon which produce photoelectrons with appropriate energy and momenta before scattering to contribute to the photocurrent[14], 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[15] surface, η_c is the barrier collection efficiency, which is bias dependent due to the image force effect and A_T is the total optical absorbance of the metal. Internal photoemission is the optical excitation of electrons in the Schottky metal to energy above the Schottky barrier and then transport of these electrons into the semiconductor. The standard theory of photoemission from a metal into the vacuum is due to Fowler[14]. In a gas of electrons obeying the Fermi-Dirac statistic, if energy photon is close to potential barrier (hν≈Φ_B), the fraction (F_e) of the absorbed photons is given by:

$$F_e = \frac{\left[\left(h\nu - (\phi_{B0} - \Delta\phi_B)\right)^2 + \frac{(kT\pi)^2}{3} - 2(kT)^2 e^{-\frac{h\nu - (\phi_{B0} - \Delta\phi_B)}{kT}} \right]}{8kTE_F \log\left[1 + e^{\frac{h\nu - (\phi_{B0} - \Delta\phi_B)}{kT}}\right]} \quad (2)$$

where hν is photons energy, Φ_{B0} is the potential barrier at zero bias, $\Delta\Phi_B$ is the lowering due to an inverse voltage applied and E_F is metal Fermi level. The previous equations were obtained without taking into account the thickness of the Schottky metal layer. In order to study the quantum efficiency for thin metal films, the theory has been further extended, taking into account multiple reflections of the excited electrons from the surfaces of the metals film, in addition to collisions with phonons, imperfections and cold electrons[15]. According to this model the accumulated probability P_e is given by:

$$P_E \cong \left[1 - \exp\left(-\frac{d}{L_e}\right)\right]^{\frac{1}{2}} \quad (3)$$

where d is the metal thickness and a L_e the mean free path. The probability that an electron travels from the metal-semiconductor interface to the Schottky barrier maximum without scattering in the silicon is taking into account by the barrier collection efficiency η_c, which is given by:

$$\eta_c = e^{-\frac{x_m}{L_s}} \quad (4)$$

where L_s and x_m are the electron scattering length and the position of the potential barrier maximum in the silicon[16] (dipending of the inverse voltage applied), rispectively. Finally, the total optical absorbance of the metal (A_T) is numerically calculated by the Transfer Matrix Method (TMM) [8]. Normal incidence condition and the restriction to variations of n(z), i. e. the unidimensional refractive index profile, along the propagation direction (z) are taken into account. In order to calculate the maximum quantum efficiency of a RCE metal Schottky barrier silicon photodetector, based on internal photoemission effect and operating at 1.55 μm, the following methodology has been adopted:

- The bottom mirror reflectivity and phase are calculated (R_2=0.99, ψ_2=3.11 rad).

- For metal thickness into the range (0-50 nm): top mirror reflectivity and phase (R1, ψ1), the value of silicon cavity thickness in resonance condition (8) and the absorbance are calculated using TMM. We obtain a curve of absorbance for metal thicknesses in the range of 0-50nm and we consider the maximum.
- Dielectric coating thickness is chosen in order to avoid perturbation of resonance condition.
- Obtained the maximum absorbance, the parameters of optimized cavity are fixed and the quantum efficiency as a function of wavelength in the range of interest is calculated using Eqs. (1-4).

The methodology takes into account the dependency of efficiency on reflectivity of the top and buried mirrors and the normalised absorption coefficient αd of the metal, while the peak wavelength is a function of cavity length (L) and of the phases shift due to the top and bottom mirror (Ψ_1, Ψ_2). The parameters calculated are summarized in the table 2.

In our device, we suppose that the metal-semiconductor junction is polarized in opposite way. It is simple to prove that for an inverse voltage of -0.85 V the depletion layer is greater than the λ/2-layer of cavity (i.e. the path that carriers generated into metal have to cross before being collected by ohmic contact).

Considering the range of bias voltage [1V-40V], the previous condition is always satisfied, therefore we can assume that the depleted region (W) is just the cavity length (W=L). Efficiency versus wavelength for the three different metals, are reported for a structure without Bragg in fig. 2 and with Bragg in fig. 3, respectively. We obtain that a significant enhancement of two order of magnitude of quantum efficiency can be achieved by using a resonant cavity structure. It is worth noting that copper has the best quantum efficiency (about 0.2%) and selectivity due to its lower potential barrier and to its higher reflectivity, respectively. It is interesting to compare also gold and silver, due to the same value of barrier we get the same order of efficiency, but in the case of gold we get a better selectivity, due to the higher reflectivity.

Maximum efficiency at the resonant wavelength versus inverse voltage applied is reported in Fig. 4. We note that for a given metal, increasing the inverse applied voltage, the quantum efficiency at 1.55 micron increases.

Table 1. Optical and electrical properties for three metals: gold, silver and copper

Metal	Complex refractive index (N)	Mean free path (L_e) [μm]	Fermi level (E_F) [eV]	Potential barrier (Φ_B) [eV]
Gold	0.174-j9.96	0.055	5.53	0.78
Silver	0.450-j9.29	0.057	5.48	0.78
Copper	0.145-j9.83	0.045	7.05	0.58

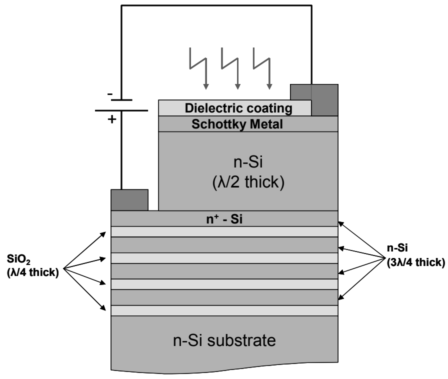

Figure 1. Schematic cross section of our RCE Schottky photodetector.

Table2. Cavity parameter coming out from our simulations

Metal	Cavity thick-ness (L) [μm]	Metal thick-ness (d) [nm]	R_1	Ψ_1 [rad]	A_T	Q value
Au	0.420	300	0.920	-2.140	0.780	525
Ag	0.410	200	0.730	-2.110	0.930	153
Cu	0.420	320	0.930	-2.360	0.740	585

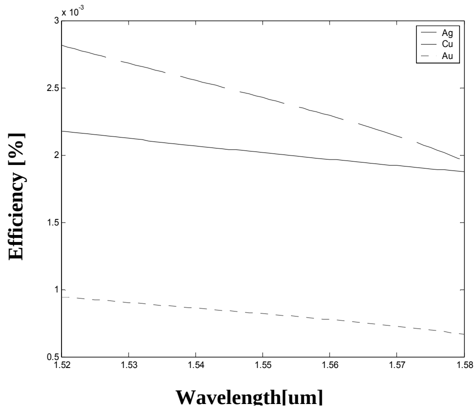

Figure 2. Calculated quantum efficiency versus wavelength for 0.85 V of inverse voltage applied for the three devices without Bragg Reflector.

substrate is maintained at liquid nitrogen temperature during the metals deposition . Even if theoretically achievable efficiency is not usable in practical applications, however, results are encouraging in order to investigate more complex structures having a higher Q value (for example ring resonator) or avalanche structures, which could provide a significant improvement of quantum efficiency. The main advantage of photodetectors is that they are fast and their fabrication process is simple and completely compatible with standard Si technology.

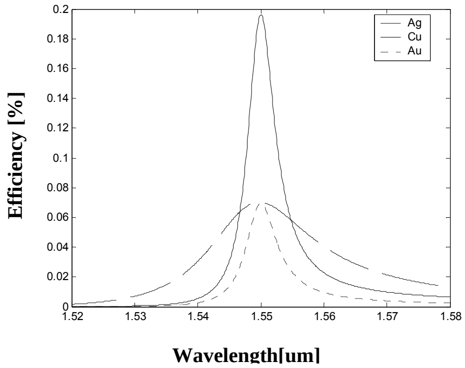

Figure 3. Calculated quantum efficiency versus wavelength for 0.85 V of inverse voltage applied

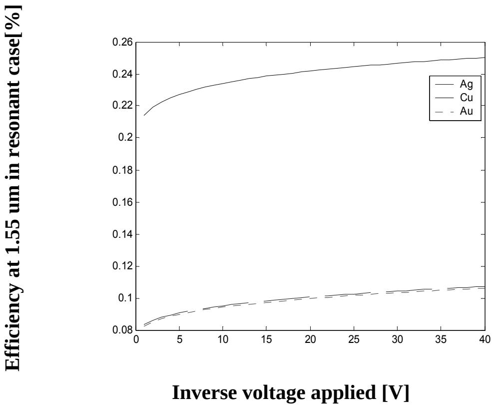

Figure 4. Calculated quantum efficiency at 1.55µm versus the inverse voltage applied.

3. CONCLUSION

In this paper, the design of a novel photodetector working at 1.55µm and completely realized in silicon is reported. The device is a resonant cavity enhanced (RCE) structure incorporating a silicon photodetector based on the internal photoemission effect.

We gave some guidelines for the best design of the device and propose a comparison among three different photodetectors, having as Schottky metal: gold, silver or copper respectively. We prove that a significant enhancement in quantum efficiency can be achieved by using a resonant cavity structure. Finally we note that for a given metal, increasing the inverse applied voltage, the quantum efficiency at 1.55 micron increases. It is worthy noting that implementing this design the fabrication could be not simple. The precise control of metal thickness in namometer (0~50nm) range and an acceptably low defect concentrations are not a trivial tasks. However, in some papers ([17], [18]) a large number of different metal-silicon contacts including gold, silver and copper,and having a metal-thickness into the range from 5 to 150 nm have been realised and characterised. It was proved that diffusion phenomena could be reasonably reduced, if the silicon

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