Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Journal of Luminescence 121 (2006) 399–402
JOURNAL OF LUMINESCENCE
www.elsevier.com/locate/jlumin

Design of a silicon RCE Schottky photodetector working at 1.55 μm

M. Casalino[a,b], L. Sirleto[a,*], L. Moretti[b], F. Della Corte[b], I. Rendina[a]

[a]*Istituto per la Microelettronica e Microsistemi (IMM), Consiglio Nazionale delle Ricerche, Via P. Castellino, 80131 Napoli, Italia*
[b]*Università degli studi "Mediterranea" di Reggio Calabria, Località Feo di Vito, 89060 Reggio Calabria, Italia*

Available online 29 September 2006

Abstract

In this paper, the design of a resonant cavity-enhanced (RCE) Schottky photodetector, based on internal photoemission effect and working at 1.55 μm, is presented. In order to estimate the theoretical quantum efficiency we take the advantage of analytical formulation of the internal photoemission effect (Fowler theory), and its extension for thin films, while for the optical analysis of device a numerical method, based on the transfer matrix method, has been implemented. Finally, we complete our design calculating bandwidth and bandwidth-efficiency product.

Our numerical results prove that a quantum efficiency of 0.1% is obtained at resonant wavelength (1.55 μm) with a very thin absorbing metal layer (30 nm). Theoretical values of 100 GHz and 100 MHz were obtained, respectively, for the carrier-transit time limited 3-dB bandwidth and bandwidth-efficiency. The proposed photodetector can work at room temperature and its fabrication is completely compatible with standard silicon technology.

Keywords: Internal photoemission; Photodetector; RCE; Silicon; DBR

1. Introduction

Silicon (Si) photodetectors have already found wide acceptance for visible light (0.400–0.700 μm) applications, while for applications in optical communications in the near-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 interband transition, a cut off wavelength of about 1.1 μm is obtained, therefore, in order to obtain photodetector working at 1.3–1.55 μm fiber optic communication wavelength range, we have two possible option. The former 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. The latter option is the exploitation of the *internal photoemission effect* over the metal-semiconductor Schottky barrier [1].

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 optical cavity allows the use of thin absorbing layers, which minimizes the transit time of the photogenerated carriers without hampering the quantum efficiency [2]. Resonant cavity enhanced (RCE) photodetectors have been successfully demonstrated for a range of operating wavelengths, including Si-based detectors optimized for 850 nm [3] and Ge-based detectors designed for operation around 1550 nm [4].

Si-based technologies provide a nice platform for the monolithic integration of optics and microelectronics. There have been some tremendous progress during the last few years in the field of Si photonics regarding light generation and light modulation obtained by all Si devices [5,6], whereas, regarding light detection, impressive results have been obtained by photodetectors based on Ge. However, the growth of this compound on Si is still a challenge in terms of cost and complexity [4]. Therefore the direct monolithic integration of photodetectors in a chip

*Corresponding author.
E-mail address: luigi.sirleto@imm.cnr.it (L. Sirleto).

0022-2313/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jlumin.2006.08.079

should be a more attractive solution to integrate receivers with electronics. The core of such photodetectors should be efficiently absorption of light in the near infrared. *Internal photoemission effect* is the only effect we can use in order to pursuit the aim of realizing all Si devices. 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. Depending on the height of the metal semiconductor barrier, the cut-off wavelength of Schottky photodiodes can be changed. *Gold* is an excellent conductor for low values of thickness, and has a high Schottky barrier (i.e., $\phi_B = 0.76\,\text{eV}$ in the case of $10^{16}\,\text{cm}^{-3}$ n-doped Si). Being $h\nu$ at the wavelength of $1.55\,\mu\text{m}$ about equal to ϕ_B, Schottky photodiodes could be useful to detect light at the communication wavelength range.

Schottky photodiodes are very attractive because of their simple material structure and fabrication process. The main advantage of Schottky photodiodes resides in their extremely high switching speed, but due to the leakage photon flux within the metallic layer, their quantum efficiency is small. In order to enhance the quantum efficiency, the RCE detection is particularly attractive for Schottky-type photodetectors, since the semitransparent metal contact can also function as the top reflector. On this line of argument, in this paper, the design of a Si Schottky RCE-PD operating at $1.55\,\mu\text{m}$, based on the internal photoemission effect, is proposed. We note that our structure is a little bit different with respect to *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. We prove that the metal layer thickness sets the maximum achievable quantum efficiency, while the $\lambda/2$-intrinsic-Si-layer sets the carrier-transit time limited 3-dB bandwidth.

2. Device structure and analysis

The device proposed is shown in Fig. 1; the RCE photodetector, working at $1.55\,\mu\text{m}$, is based on internal photoemission effect over a Schottky junction Au–Si, top illuminated. 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 $\lambda/2$-intrinsic-Si-layer.

The buried reflector is a Bragg mirror formed by alternating layers of different refractive indices. One of the many benefits of Si is the large index contrast provided by Si–SiO_2 structures, allowing the realization of high-reflectivity, wide spectral stop-band distributed Bragg reflector (DBR) made of few periods. Anyway, limitations in fabrication process usually do not allow for layer thickness as thin as ($\lambda/4n$), for this reason ($3\lambda/4n$) layers for Si were utilising [7]. Starting from this results, in our design we propose a DBR centered at $1.55\,\mu\text{m}$. The DBR could be formed by alternate layers of Si and SiO_2 having refractive index 3.45 and 1.45, and thickness of 340 and 270 nm, respectively. In our design a bottom mirror formed by 4 periods of Si/SiO_2 is considered. In order to get ohmic contact, the top layer of the DSOI is supposed to be realized by a very thin but heavily doped $10^{19}\,\text{cm}^{-3}$ Si layer.

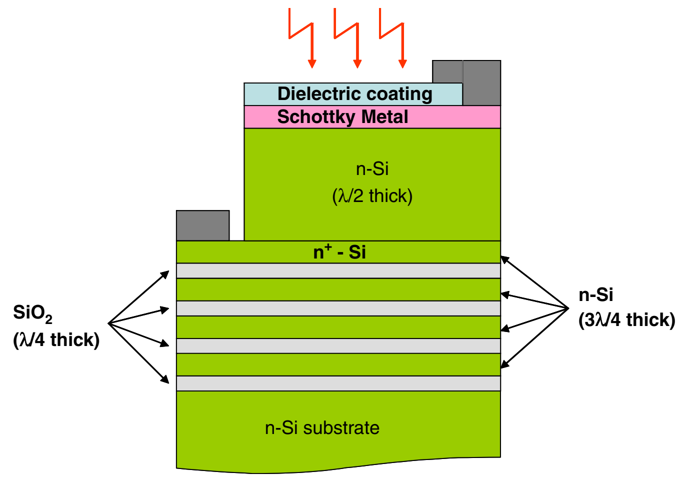

Fig. 1. Schematic cross-section of the proposed photodetector.

A semitransparent Schottky metal and a dielectric coating layer for passivation and protection purpose, deposited on $\lambda/2$ Si layer, works as the top reflector of the resonant cavity. We choice gold as the Schottky metal having refractive index $N_{Au} = 0.174 + j9.96$, mean free path $L_e = 0.055\,\mu\text{m}$ and Fermi level $E_F = 5.53\,\text{eV}$. The dielectric coating is a Si_3N_4 layer, having refractive index 2.0.

Quantum efficiency: The *quantum efficiency* can be obtained by the formula [8]

$$\eta = A_T F_e P_E, \tag{1}$$

where A_T is the total optical absorbance of the metal that is the fraction of photon absorbed, F_e is the fraction of the absorbed photons which produce electrons with the appropriate energy and momenta before scattering and P_E is the total accumulated probability that one of these electrons will be able to overcome potential barrier after scattering.

The standard theory of photoemission from a metal into the vacuum is due to *Fowler* [9]. In a gas of electrons obeying the Fermi–Dirac statistic, if energy photon is close to potential barrier ($h\nu \approx \Phi_B$), the fraction (F_e) of the absorbed photons is given by:

$$F_e = \frac{N_B}{N_A} = \frac{[(h\nu - \phi_B)^2 + (kT\pi)^2/3]}{8kTE_F\,\log\left[1 + e^{h\nu - \phi_B/kT}\right]}, \tag{2}$$

where $h\nu$ is photons energy, ϕ_B is the potential barrier 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 [8]. According