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Tunable infrared photoemission sensor on silicon using SiGe/Si and silicide/Si epitaxial layers

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Abstract: We present a new type of infrared detector on Si whose cut-off wavelength is tuned by an externally applied bias. This tunable internal photoemission sensor (TIPS) consists of two different conducting materials (metal or degenerately doped SiGe) separated by a thin undoped Si layer. The two conducting materials are chosen with different barrier heights on Si so that the depleted Si layer forms an asymmetrical potential barrier. Under sub-band gap illumination, carriers (both holes and electrons) which are photocreated in each conducting film, cross the Si barrier and give rise to a photocurrent between the two electrodes. This photocurrent is strongly dependent on the shape and height of the Si potential barrier that can be varied by a small bias applied between the two electrodes. In this paper, the TIPS principle of operation and the photoresponse tunability are demonstrated using both the Ir/Si/ErSi₂ and Cr/Si/SiGe (p+) heterostructure.

1. Introduction

The internal photoemission (IPE) of carriers over a silicide-silicon Schottky barrier,^(1,2) or the valence band discontinuity of SiGe/Si heterostructures,⁽³⁾ has been widely used for infrared detection on Si. Thanks to advances in Si technology, large focal plane arrays based on PtSi/Si Schottky diodes with a 6 μm cut-off wavelength have been routinely fabricated.⁽²⁾ Recently, IPE cut-off wavelengths larger than 12 μm have been demonstrated using IrSi/Si⁽¹⁾, PtSi/Si⁽⁴⁾ and SiGe/Si⁽³⁾ detectors. However, all these devices have their cut-off wavelength fully determined by the potential barrier height at the heterojunction. That barrier height which is fixed by the fabrication parameters cannot be externally modified except for the Schottky barrier lowering which only allows a tuning range of a few tens of meV. In contrast, one could expect a much larger modulation effect,⁽⁵⁾ more than several hundred meV by using an asymmetrical potential barrier sandwiched between two metals or degenerately doped semiconductor layers. Indeed, the shape of that barrier formed by an intermediate undoped semiconductor can be modified by a small bias, thus varying the spectral profile of the photoresponse as well as the cut-off wavelength.

2. Silicide based TIPS

The Ir/Si/ErSi₂ TIPS basically consists of two back-to-back Schottky diodes separated by a thin undoped Si layer. The thickness of this Si layer is adjusted so that the Si is fully depleted, resulting in a potential barrier between the two metallic films. The two metals are chosen with different Schottky barrier

heights (SBHs) on silicon (a SBH on n-type Si of around 0.9 eV for Ir⁽⁶⁾ and 0.3 eV for ErSi₂⁽⁷⁾) so that the TIPS exhibits a highly asymmetrical band structure (Figure 1). Under infrared illumination, a fraction of the photoexcited carriers may overcome the Si potential barrier, giving rise to four different internal photoemission processes between the two electrodes.⁽⁵⁾

First, two photocurrents of the same sign are present and similar to the photocurrent observed in a Schottky detector: holes (photocurrent I_1) emitted below the ErSi₂/p-Si barrier, (since in Figure 1 increasing hole energy is directed towards the bottom) will drift down the built-in electric field before being collected in the Ir film and electrons (photocurrent I_2) emitted above the Ir/n-Si barrier, will cross the Si layer before being collected in the ErSi₂ film.

Figure 1 : Schematic energy band diagram of the Ir/Si/ErSi₂ TIPS with no applied bias. The four photoemission processes described in the text are represented : I_3 and I_4 are specific to the TIPS structure, while the other two processes, I_1 and I_2 , are similar to those observed in Schottky diodes.

Figure 2 : Quantum efficiency of an Ir(20nm)/Si(190nm)/ErSi₂(10nm) TIPS, measured at 150 K, as a function of photon wavelength (back illumination) for different positive biases applied between the Ir and ErSi₂ electrodes. The solid lines are the theoretical curves obtained using the model derived from the Fowler formalism and described in the text.

In addition, two other photocurrents, specific to the TIPS structure and having opposing signs to those of I_1 and I_2 are observed: electrons (photocurrent I_3) excited in the ErSi₂ film, are emitted above the ErSi₂/n-Si barrier, cross the Si film against the built-in electric field and are collected in the Ir electrode. The threshold of this specific TIPS photocurrent can be described with an effective barrier height (EBH) which, in a first approximation (a more precise analysis would take into account the hot carrier scattering in Si), is equal to the sum of the ErSi₂/n-Si SBH and the potential drop present in the Si layer. This potential drop can be modified with a small external bias applied between the two metallic films, thus modulating the threshold of the photocurrent I_3 . The other specific TIPS photocurrent is the photocurrent I_4 of holes photoemitted from Ir to ErSi₂ that mirrors I_3 and therefore also presents a tunable threshold.

The respective magnitude of these four photocurrents depends primarily on the photon energy but also on the applied bias through the modification of the potential barrier. In addition to the threshold modulation, one could also expect a significant modulation of the intensity and shape of the TIPS photoresponse.

Details on the epitaxial growth of the ErSi₂/Si heterostructures and TIPS fabrication can be found in reference 8 and 9 respectively. Figure 2 shows the TIPS quantum efficiency versus wavelength, under back illumination, for different positive biases applied between the two metallic electrodes (positive bias on the Ir electrode with respect to the ErSi₂ one). This figure clearly demonstrates that: i) both the shape and intensity of the TIPS quantum efficiency depend dramatically on the applied bias, and ii) the cut-off wavelength increases with increasing applied bias.

The TIPS photoresponse exhibits behaviour that cannot be explained by the usual Fowler formalism⁽¹⁰⁾ (i.e. photocurrent proportional to $(h\nu - \phi)^2$ where ϕ is the SBH). This indicates that the origin of the TIPS photocurrent is more complex: indeed, i) four different internal photoemission processes are simultaneously in competition, and ii) due to the multilayer structure and contrary to the case of Schottky diodes, the TIPS absorption is strongly dependent on the photon energy. Indeed, transmission measurements⁽⁹⁾ show a minimum near 1.6 μm in the relative absorption of the ErSi₂ film. This qualitatively explains the quantum efficiency dip (Figure 2) and arises from the Fabry-Pérot cavity formed by the multilayer system.

In order to quantitatively describe the TIPS quantum efficiency, we modify the usual Fowler model and describe the quantum efficiency Y as the sum of the four contributions:

$$Y = |Y_1 + Y_2 - Y_3 - Y_4| \quad \text{with} \quad Y_i = A_i f_{\text{abs}}^i (h\nu - \phi_{\text{eff}}^i)^2 \alpha_i$$

where A_i is a constant function of the metal from which hot carriers are created,⁽¹⁰⁾ $f_{\text{abs}}^i(h\nu)$ is the fraction of the incident light absorbed into the metal from which the photocurrent originates, $(h\nu - \phi_{\text{eff}}^i)^2$ results from the usual Fowler theory, with the SBH replaced by an EBH ϕ_{eff}^i , and α_i is the transfer ratio of hot carriers crossing the Si barrier. The transfer ratio α_i depends on the applied bias through the characteristics of the hot carrier relaxation mechanisms in the Si: α_i is nearly equal to unity for the "Schottky" photocurrents, I_1 and I_2 (the carriers are swept by the electric field); α_i is lower than unity for the "TIPS" photocurrents, I_3 and I_4 , increases with bias and tends towards unity for a bias higher than the flat band bias.

The photocurrents are calculated using the EBHs ϕ_{eff}^i and the transfer ratio α_i as fitting parameters. Since the photocurrents I_1 and I_2 have large SBH, their contribution is noticeable only for short wavelengths and small or negative applied biases. The fits, depicted by the solid lines in Figure 2, have therefore been obtained with contributions from the two photocurrents I_3 and I_4 only. The very good agreement between experiment and calculation confirms the existence of both electron and hole photocurrents in this asymmetric heterostructure. Furthermore, this indicates that transport of hot electrons and holes occurs in the epitaxial Si layer over distances as large as 200 nm.

Figure 3 : Variations in ϕ_{eff}^3 (●) and ϕ_{eff}^4 (◆) with positive applied bias deduced from the data of Figure 2 using the modified Fowler formalism. The variation in ϕ_{eff}^4 deduced from the I-V characteristics (◊) is also shown for comparison.

Secondly, this procedure allows accurate determination of the EBHs as a function of the applied bias. As expected, the values of ϕ_{eff}^1 and ϕ_{eff}^2 (obtained by fitting the negatively biased photoresponse) are found to be independent of the applied bias, except for the slight Schottky barrier lowering, and equal to the SBHs ϕ_1 and ϕ_2 respectively. This result agrees with standard photoemission observations in Schottky diodes.⁽⁷⁾ On the other hand, the EBHs of the two specific TIPS photocurrents, ϕ_{eff}^3 and ϕ_{eff}^4 , decrease with applied bias and tend towards ϕ_3 and ϕ_4 respectively as shown in Figure 3. We emphasise that the EBH variations are more than an order of magnitude larger than those observed in the Schottky diodes. The decrease in the smallest EBH (ϕ_{eff}^4) with positive bias explains the shift in the TIPS cut-off wavelength that can thus be tuned to more than 6 μm .

The TIPS current-voltage characteristics exhibit behaviour similar to that of a Schottky diode and can be quantitatively explained by the same TIPS model. We now take into account four thermionic currents (instead of photocurrents) of electrons and holes. Therefore the EBH ϕ_{eff}^4 can also be determined by the slope of the J/T^2 versus $1000/T$ curves (where J is the total TIPS current density). We note that the ϕ_{eff}^4 variations with applied bias determined by both optical and electrical measurements are in satisfying agreement (Figure 3) and confirm the tunability of such an asymmetric heterostructure. Finally, from the measured responsivity and experimental dark current (I_{dark}) and using the "shot-noise" expression $B = \sqrt{2 q I_{\text{dark}}}$ for an ideal detector, the upper limits of TIPS detectivity were found to be equal to $1.5 \times 10^9 \text{ cm} \sqrt{\text{Hz}} / \text{W}$ at $2 \mu\text{m}$ at 125 K under a forward bias of 0.3 V.

3. SiGe based TIPS

The TIPS principle of operation can be extended to a metal/Si/SiGe(p+) heterostructure: the underlying ErSi₂ film is replaced by a boron doped ($\sim 10^{20} \text{ cm}^{-3}$) SiGe layer (around 15% Ge concentration), and the top metallic film by Cr giving the asymmetrical band structure of Figure 4. The SiGe TIPS uses the same physical detection process as that of the silicide with only three IPE photocurrents: two of them (hole photocurrent I_1 and electron photocurrent I_2) are specific to the TIPS structure (their threshold can be modified by an external applied bias) whereas the third (hole photocurrent I_4) is similar to that observed in a Schottky detector. In addition to the photoresponse and cut-off wavelength modulations, one could expect with the SiGe TIPS : i) an improved crystalline quality since the epitaxial growth of SiGe is perfectly controlled and of very good quality^(11,12), ii) an important increase in the cut-off wavelength towards higher wavelengths since the maximum cut-off wavelength is fixed by the valence band discontinuity between the strained SiGe layer and the underlying Si (of the order of 100 meV for around 15% Ge concentration), and iii) an increase in the quantum efficiency since in the long wavelength range, single SiGe/Si heterojunctions outperform silicide Schottky detectors.⁽³⁾

Figure 4 : Schematic energy band diagram of the Cr/Si/SiGe(p+) TIPS with no applied bias. The three photoemission processes are represented : I_1 and I_2 are specific to the TIPS structure while I_4 is similar to that observed in a Schottky diode.

Figure 5 : Spectral photoresponse of a Cr(20nm)/Si(100nm)/SiGe(20nm) TIPS, measured at 20 K, as a function of photon wavelength (back illumination) for different negative biases applied between the Cr and SiGe electrodes.

The SiGe TIPS were epitaxially grown either by RT-CVD [11] or by UHV-RTCVD [12] on 4-in. $\langle 100 \rangle$ Si 8–15 Ωcm wafers. Figure 5 shows the first spectral photoresponse of a typical SiGe TIPS measured for different biases applied between the Cr and SiGe electrodes (negative bias on Cr with respect to SiGe). This figure shows that at zero or positive applied bias an abrupt cut-off at around $2.5 \mu\text{m}$ is

observed. A Fowler analysis of this photocurrent gives a SBH of 500 meV which corresponds to the Cr/p-Si barrier. For negative biases, the photocurrent changes sign and presents a broad peak at around 5 μm . This peaked photoresponse is similar to that observed in a single SiGe/Si heterostructure⁽³⁾. It results from the trade off between the free carrier absorption in the SiGe layer which increases with wavelength and the IPE process whose efficiency decreases with wavelength. The very large cut-off wavelength now corresponds to the smallest barrier SiGe/Si. For high negative biases, the peak broadens increasing the cut-off wavelength towards higher wavelengths (around 10 μm). This increase in cut-off wavelength can be explained by a lowering of the SiGe/Si barrier with applied bias.

Figure 6 shows the forward I-V characteristics measured in the dark from room temperature down to 77K for a typical SiGe TIPS detector of 0.174 mm² active area. The I-V characteristics exhibit, at low bias, behaviour similar to that of a Schottky diode. In contrast, at high bias, the current is dominated by the series-resistance. These I-V characteristics can be quantitatively fitted using the TIPS model by taking into account three thermionic currents of electrons and holes. For positive applied biases, the electron EBH is much larger than those of the hole and its contribution to the total current is negligible. The TIPS current is therefore the sum of the two hole currents of opposing signs. For applied biases lower than the flat-band bias (where the potential drop equals zero), each hole current density is equal to:

$$A^* T^2 \exp\left(-\frac{q \Phi_{\text{eff}}^i}{k T}\right)$$

where, A^* is the Richardson constant, $\Phi_{\text{eff}}^4 = \Phi_4 - \Delta\Phi_4$ for the current i_4 , $\Phi_{\text{eff}}^1 = \Phi_4 - \Delta\Phi_4 - V$ for the current i_1 , $\Delta\Phi_4$ (which is $V^{1/2}$ in the TIPS structure) is the barrier lowering due to the image-force effect⁽¹³⁾.

The current, calculated with this model and taking into account a series-resistance of around 1000 Ω and an ideality factor close to unity, is depicted by the solid lines in Figure 6 and is in good agreement with experimental data for the whole temperature range. We note that in the high bias region and below 150 K, the current is actually not limited by the series-resistance which is almost independent of temperature but is limited by the smallest barrier height, Φ_1 , which is reversed biased.

Figure 6 : Forward I-V characteristics measured in the dark from 293 to 77 K of a typical SiGe TIPS detector. The solid lines are obtained using the electrical model described in the text.

Figure 7 : Forward I-V characteristics at 20K for a typical SiGe TIPS in the dark ($\diamond$) and with the 300K radiation background ($\blacklozenge$).

The TIPS tunability can be observed by simple current–voltage measurements at 20K in the dark and with the 300K radiation background (Figure 7). For I–V characteristic in the dark, the current is roughly flat until 600 mV (small increase due to the barrier lowering by the electric field) before increasing dramatically. This sharp increase is clearly a leakage current probably resulting from defects at the heterojunction interface. With the 300K radiation background, a plateau of around 1 nA at biases between 400 and 650 mV can be observed before the sharp increase in the current. If we consider that a 300K radiation background is essentially composed of very low energy photons, this plateau is a photocurrent plateau resulting from absorption of these photons. For biases higher than 400 mV, the TIPS is sufficiently biased to detect low energy photons since the hole photocurrent from SiGe to Cr with the smallest barrier height ϕ_1 can dominate. The occurrence of this photocurrent plateau only above 400 mV and not at zero bias as in a simple Schottky type detector, is a direct consequence of the SiGe TIPS band structure. It is a remarkable observation since it confirms, purely by I–V measurements, the tunability of the TIPS cut-off wavelength.

4. Conclusion

We have reported a new tunable infrared photosensor based on the photoemission of excited carriers above an asymmetrical potential barrier. The silicide TIPS photoresponse has been quantitatively explained: the tunability originates from the EBH variation (which is more than 10 times larger than the standard Schottky barrier lowering) with the external applied bias. I–V measurements also confirm the wavelength tunability and indicate that high detectivities may be expected with the TIPS structure. Furthermore, the SiGe based TIPS allows the TIPS tunability to be combined with the extended wavelength range (above 10 μm).

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