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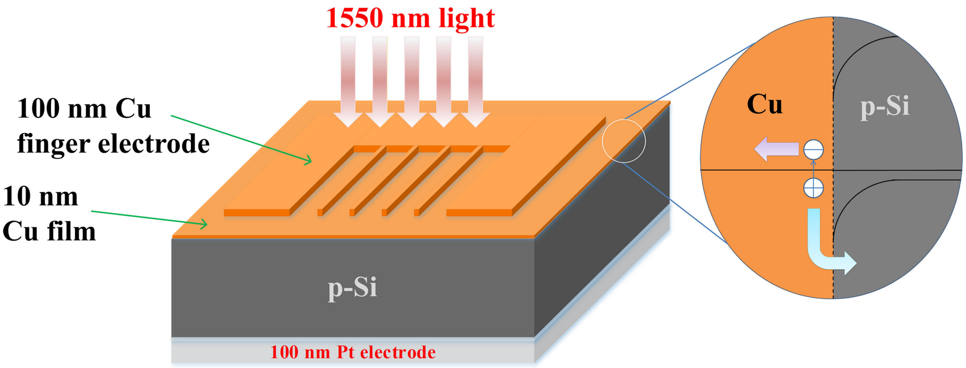
Yu-Chieh Huang
Vivek Parimi
Wei-Che Chang
Hong-Jhang Syu, *Member, IEEE*
Zih-Chun Su
Ching-Fuh Lin, *Fellow, IEEE*



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Yu-Chieh Huang, Vivek Parimi, Wei-Che Chang,
Hong-Jhang Syu, *Member, IEEE*, Zih-Chun Su,
and Ching-Fuh Lin, *Fellow, IEEE*

[1]Graduate Institute of Photonics and Optotelectronics, National Taiwan University, Taipei 106319, Taiwan
[2]Graduate Institute of Electronics Engineering, National Taiwan University, Taipei 106319, Taiwan
[3]Department of Electrical Engineering, National Taiwan University, Taipei 106319, Taiwan
[4]Center for Electronics Technology Integration, National Taiwan University, Taipei 106319, Taiwan

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Abstract: In this work, the design and fabrication of a Cu/p-Si/Pt Schottky photodetector with a simple structure is investigated. The mechanism of electron flow is explained using internal photoemission theory, which is further applied to make the fabricated devices reach a high responsivity of 0.542 mA/W at 0–V bias. The investigation revealed that the rapid thermal annealing process could significantly influence the device characteristics. Variations in Schottky barrier height and series resistance of the photodetectors were also analyzed and correlated with the device responsivity. With proper conditions to improve the Pt/Si ohmic contact, the device performance can be enhanced.

Index Terms: Annealing, optical communication, photodetectors, photodiodes, silicon photonics, semiconductor device manufacture.

1. Introduction

Recently, photodetectors in optical communication range with Si-based chips have attracted increasing attention. For CMOS-compatible photodetectors, Si substrates are necessary. However, Si-based photodetectors, which are widely used in the visible spectral range, are typically unsuitable for detecting the telecommunication wavelength region (1.3–1.6 μm) because the energy of an infrared photon is lower than the bandgap of Si (1.12 eV). To overcome this issue, various designs have been proposed before. A Ge-based photodetector in the near-infrared (NIR) wavelength range, a decent option for detection due to its bandgap (0.6 eV) being lower than the energy of optical communication bands, has the disadvantages of being less compatible with Si chips due to thermal mismatch stress and costly processes [1]–[5]. To make Si-based photodetectors for infrared wavelengths possible, some prevalent technologies for Si-based photodetectors for sub-bandgap infrared ranges were developed, including mid-band absorption (MBA) [6], [7] surface-state absorption (SSA) [8], [9] and two-photon absorption (TPA) [10], [11]. In the case of the nanofabrication process for MBA, a high concentration of impurities and structural defects are usually incorporated into the Si lattice. This can increase the responsivity of the device but can also have detrimental effects on the device performance over time. When SSA is utilized for photodetection, the response of the device is often highly sensitive to temperature changes, which makes it unsuitable for industrial applications. The major drawback of TPA is that it is a very weak mechanism and often has a very low quantum efficiency. Moreover, the production of these complicated device geometries is quite expensive.

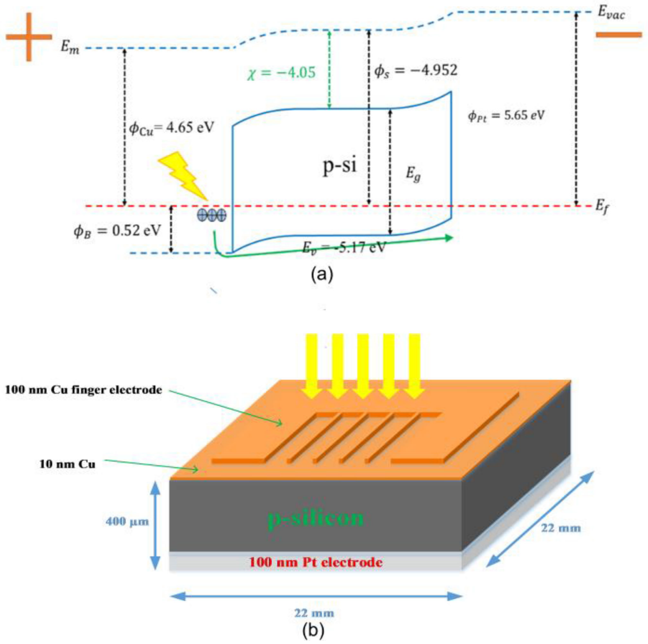
To mitigate those issues, internal photoemission (IPE) [12] based photodetectors are a viable option to produce low-cost NIR all-Si photodetectors [13]–[15]. The Schottky barrier is lower than the bandgap of Si and can detect longer wavelengths in the NIR range. The main advantages of using a Schottky-barrier-based photodetector are the simplicity of its fabrication, large bandwidth, and high-frequency response due to the fast thermalization time of excited electrons in the metal. Previous works based on Cu/p-Si photodetectors demonstrated that maximum responsivity at 1550 nm is 0.002 mA/W at 0-V bias [15]. Another study on Cu/Si photodetectors for infrared range [16] depicts a maximum responsivity of 8 μA/W. According to Casalino *et al.* [15], one of the major causes for low responsivity of photodetectors was the poor quality of ohmic contacts, which lowered the efficiency of the collection of the photogenerated carriers. In this work, a compact and efficient Cu/p-Si Schottky photodetector with platinum electrodes for optical detection at 1550 nm displaying a maximum responsivity of 0.542 mA/W at 0-V bias has been demonstrated. We analyze the Schottky barrier height and series resistances of the devices using thermionic emission theory and explain the mechanism of the operation of the photodetector using IPE. Based on the analysis, we are able to improve the device performance, greatly enhancing the responsivity.

2. Experimental Details

The Schottky photodetector works on the principle of IPE, which is the phenomenon of excitation of carriers from the metal using photons to overcome the potential of the Schottky barrier and the transport of these carriers to the valence band of the semiconductor, as demonstrated in Fig. 1(a). This results in a photocurrent flowing through the device that can be measured and used to detect radiation of a particular energy level. The standard theory of photoemission from a metal into a vacuum was put forward by Helman [12] based on Fowler's hypothesis [17]. The fabrication of the photodetectors was carried out mainly using an electron-gun evaporation setup (ULVAC, Inc., Kanagawa, Japan) to deposit the Cu and Pt thin films as the Schottky and ohmic contact (anode electrode), respectively. Before evaporation, the p-type Si substrates were ultrasonically cleaned with acetone, isopropyl alcohol, and deionized water, successively, to clean the surface of the Si and remove organic impurities. The substrates were then subjected to Piranha solution (200 mL $H_2SO_4 + 50$ mL H_2O_2) treatment followed by treatment with a buffered oxide etchant (BOE). This ensures a smooth surface for the formation of ohmic or Schottky contact without contaminants. In addition, a 100-nm-thick Cu layer was deposited in an interdigitated geometry on Cu Schottky contact to facilitate carrier collection as well as the incidence of light on the device (Fig. 1(b)).

3. Results and Discussion

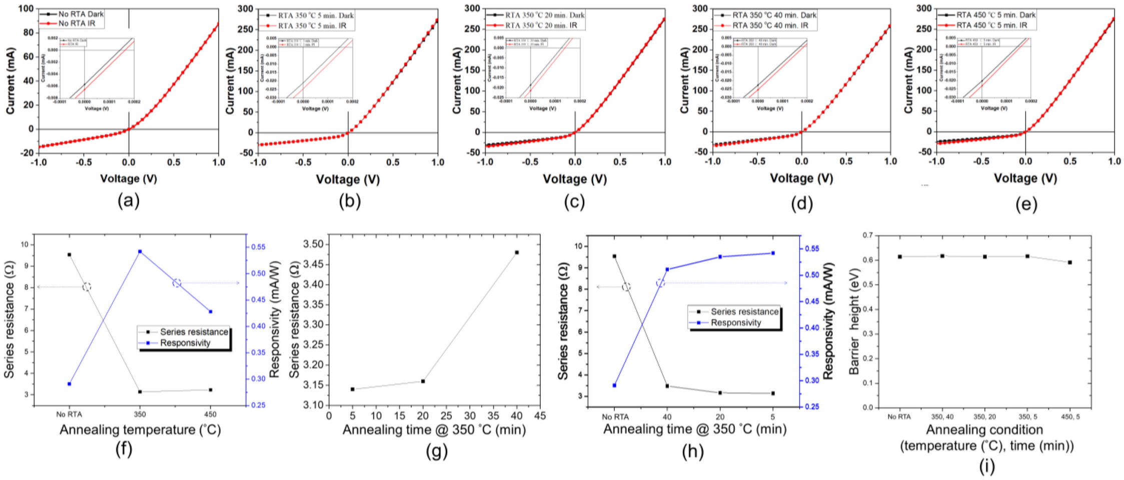
The I–V characteristics of the Cu/p-Si/Pt Schottky photodetector for DC bias voltages ranging from -1 V to $+1$ V under dark and 1550-nm continuous wave (CW) laser (ITC4005QCL, Thorlabs, Inc., Newton, New Jersey, USA) were measured using a Keithley 2400 Source Meter (Tektronix, Inc., Beaverton, Oregon, USA). The current in the device under dark condition is termed the dark current, and the current in the device when 1550-nm CW laser illuminated is the light current. The response current is the absolute difference between the light and dark currents. The responsivity is the response current divided by the power of incident radiation (3 W). In the beginning, according



(a)

(b)

Fig. 1. (a) Energy band diagram of the Schottky photodetector. (b) Schematic of the photodetector.



(a) (b) (c) (d) (e)

(f) (g) (h) (i)

Fig. 2. (a), (b), (c), (d), and (e) are I-V curves and zero bias response (inset) of fabricated photodetectors with the conditions of no RTA, RTA at 350 °C for 5 min, RTA at 350 °C for 20 min, RTA at 350 °C for 40 min, and RTA at 450 °C for 5 min, respectively. (f), (g), (h), and (i) are variation of device resistance and responsivity with respect to annealing temperature, device series resistance with respect to annealing time at 350 °C, device series resistance and responsivity with respect to annealing time at 350 °C, and barrier height with respect to each annealing condition, respectively.

to Fig. 2(a), the response current of the Cu/p-Si/Pt Schottky photodetector in 0 V without any additional treatment is calculated to be 0.873 mA. The responsivity of the device is 0.291 mA/W.

During the measurement of the Cu/p-Si/Pt Schottky photodetector above, it was found that the device has good response at 0-V bias and the reverse-bias current is smaller than the forward-bias current in the voltage with the same absolute value, which is indicative of diode I–V characteristics.

TABLE 1
Schottky Barrier Height, Series Resistance, Responsivity, and Rise Time at 0 V of Various Photodetectors

Annealing condition (temperature, time)	Schottky barrier height (eV)	Series resistance (Ω)	Responsivity (mA/W)	Rise time (μs)
No RTA	0.614	9.54	0.291	2.72
350 °C, 40 min.	0.617	3.48	0.511	0.994
350 °C, 20 min.	0.614	3.16	0.535	0.903
350 °C, 5 min.	0.616	3.14	0.542	0.897
450 °C, 5 min.	0.591	3.23	0.428	0.923

However, the positive bias current value is only slightly more than 80 mA at 1 V, which is much lower than expected. This has been attributed to the poor conductivity of the Pt/Si ohmic contact, which limits the current and response of photodetector. To mitigate this, the rapid thermal annealing (RTA) process was introduced at the Pt/Si ohmic contact. The Pt/Si ohmic contact was annealed before the deposition of the Cu Schottky contact so that no damage was done to the Schottky contact by the annealing process.

The Cu/p-Si/Pt Schottky photodetector was fabricated according to the process described above and then subjected to the RTA process under different conditions. The Pt/Si contacts treated using the RTA (e1200-RTP, Premtek, Hsinchu City, Taiwan) process under different conditions were 350 °C for 40, 20, and 5 min and 450 °C for 5 min.

According to literature, when a Pt film on a Si substrate is annealed (450–600 °C, 30 min), platinum silicide (PtSi) is formed on the surface. This process is carried out in an oxygen-free and nitrogen-rich environment, because oxides of Si will isolate the formation of PtSi [18]. Another study shows that the use of the RTA process at 200–450 °C in a nitrogen environment can produce a PtSi film of good quality [19]. At higher temperatures, the PtSi film is thicker. However, when the temperature exceeds 950 °C, the PtSi resistance increases due to the grain aggregation effect [20]. At room temperature, the Pt film is rapidly thermally annealed on the Si substrate, and the PtSi compound formed at the interface can significantly improve the ohmic contact between Pt and Si and reduce the resistance of the device [21]–[23]. Under RTA process conditions, the Pt/Si ohmic contact is enhanced, thereby reducing the resistance of the device. The photo-emitted carriers are efficiently transmitted to the electrodes after crossing the Schottky barrier, improving the performance of the photodetectors [24].

In Fig. 2(b)–2(e), the I–V curves of the RTA processing element at 350 and 450 °C are shown. The positive bias current response is significantly higher in the photodetector with RTA than in the photodetector without RTA. The current at 1 V forward bias reached a value of about 275 mA with RTA, whereas it was around 88 mA without RTA. Table 1 shows the responsivity of the photodetectors processed under various RTA conditions.

From the I–V curves, we calculated the Schottky barrier height and resistance of the photodetector. According to the thermionic emission theory, carriers with energy greater than the potential of the Schottky barrier will cross the barrier provided they move toward the barrier. From to the thermionic emission theory [25], the forward bias I–V characteristic [26] of the photodetector is as follows:

$$I = AA^{*}T^{2}\exp\left(\frac{-q\varphi_B}{kT}\right)\exp\left(\frac{qV_d}{nkT}\right) \tag{1}$$

where V_d is the voltage across the metal-semiconductor interface of Schottky photodetector; A is the area of the active region; A^* is Richardson constant and equal to 32 A-cm^2/K^2 for p-Si substrate; T is device temperature in Kelvin; q is an electron charge; Φ_B is Schottky barrier height; k is Boltzmann constant; n is ideality factor. Solving V_d from the (1) can obtain

$$V_d = \frac{nkT}{q} \ln\left(\frac{I}{AA^* T^2}\right) + n\phi_B \tag{2}$$

Furthermore, considering the device series resistance (R_s), the applied voltage or experimentally measured voltage in the Schottky photodetector circuit should be modified as

$$V = \frac{nkT}{q} \ln\left(\frac{I}{AA^* T^2}\right) + n\phi_B + IR_s \tag{3}$$

The I–V curve data shown in Fig. 2 were fit to the above equation to calculate the experimental value of the Schottky barrier height and series resistance of the photodetectors.

The I–V measurements were carried out to investigate the effect of infrared light on the electrical characteristics of the Cu/p-Si/Pt photodetectors under dark and illuminated conditions. The extent of increase in current when illuminated is higher at a larger bias voltage. This change of the Cu/p-Si/Pt photodetector is a conventional tendency of a photodiode [27], [28]. According to the fitting data, the values of the Schottky barrier height and the series resistance were determined.

Annealing significantly influences the device performance. Here the ohmic contact, the interface between Pt and Si as shown in Fig. 1(a) with RTA gives photodetectors better performance, especially annealed at 350 °C. It can be clearly observed that the series resistance of the photodetector without RTA is much higher and therefore shows a much lower response. This could be explained by the formation of PtSi at the ohmic interface, which lowers the resistance. It is observed in Fig. 2(f) that the resistance is lower at 350 °C than at 450 °C. In the case of RTA at 350 °C, the interface between Pt and Si, as shown in Fig. 1(b) has PtSi as well as Pt_2Si [29]. When RTA is conducted at 450 °C, pure PtSi is formed at the interface, which worsens the quality of the ohmic contact. This is because the conductivity of Pt_2Si is much higher than that of PtSi [30]. For annealing at 350 °C, it is also observed that the resistance is higher when the time of annealing is increased, as shown in Fig. 2(g). We hypothesize this observation to be due to the higher probability of conversion of Pt_2Si to PtSi when the annealing time increased. This, in turn, increased the resistance. A correlation between the resistance and the responsivity of the photodetector is observed at 350 °C. (Fig. 2(h))

The devices processed under different conditions either with or without RTA display the barrier height of approximately 0.6 eV as shown in Fig. 2(i), which is in accordance with the Schottky–Mott theory [31], [32]. Ideally, the annealing temperature should not affect the barrier height at Schottky contact, the interface between Cu and Si, as shown in Fig. 1(b). Since Cu electrode was evaporated on the Schottky contact after the ohmic contact is annealed by RTA. However, the temperature of annealing does have an effect to make some difference. The barrier height when annealed at 450 °C is lower than that annealed at 350 °C for 200 meV. A possible explanation for this observation is that the carrier lifetime of silicon reduces with the increase of annealing temperature up to 450 °C [33]. This is due to an increase in carrier mobility and larger drift velocity. A larger carrier drift velocity can reduce the Schottky barrier height due to quantum coupling effects [34]. Although the barrier height is lower when annealed at 450 °C, it does not have better response than that annealed at 350 °C because of larger resistance, as shown in Fig. 2(f). When RTA is conducted at 450 °C, pure PtSi formed at the interface not only worsens the quality of the ohmic contact but also reduces the response current of the device. This has the same correlation with the variation of resistance when the time of annealing is increased at 350 °C.

The Cu/p-Si/Pt photodetector that was RTA processed at 350 °C for 5 min displayed the highest responsivity of 0.542 mA/W at 0-V bias. This is much higher than the responsivity of the device that did not undergo the RTA process, which was 0.291 mA/W. Also, to evaluate the response speed, the rise time of each device was evaluated [35] and expressed in the righter most column of Table 1. The device with RTA processed at 350 °C for 5 min has the rise time of around 0.9 μs, while the device without RTA treatment has the rise time of 2.72 μs. That is, the response speed of the former one is faster than that of the latter one. It is because the RTA treatment provides a conductivity and lattice transition region between Pt and p-Si, and improves the response speed. In addition, if the device area can be reduced, the rise time can be further decreased, even less than nanoseconds. When these results are compared with previous Schottky photodetectors based on Cu and Si [15], [16], we see that the response is much higher in the RTA-processed Cu/p-Si/Pt photodetectors. The major drawback that resulted in lower responsivity was the poor quality of the ohmic contact, which was mitigated by using the RTA process. In addition, there is an added advantage of the simplicity of the structure, which makes it easier to produce planar Schottky photodetectors for commercial applications.

4. Conclusion

In conclusion, a Cu/p-Si/Pt Schottky photodetector based on IPE has been explored. Although the device has a very simple configuration, it displays a high responsivity of 0.542 mA/W at 0-V bias. Our investigation reveals that the RTA process for the ohmic contact interface of Pt/Si is very critical and can effectively improve the responsivity of the photodetectors. Analysis of the barrier height and series resistance is also consistent with the variation in the responsivity of the photodetectors annealed at different temperatures. The response of this device is much better than previously studied devices. In particular, the structure is very simple and inexpensive for possible production on a large scale.

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