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Ultrafast and high-sensitivity photovoltaic effects in TiN/Si Schottky junction

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Abstract

Ultrafast photovoltaic effects with high sensitivity in both vertical and lateral directions have been observed in the TiN/Si Schottky junction. The open-circuit vertical photovoltage across the junction is 400 mV under irradiation of an HeNe laser with a power of 7 mW. The response speed is in the picosecond order. Furthermore, we found a large lateral photovoltage (LPV) parallel to the plane of the junction. The LPV between the two electrodes on the Si substrate of the junction depends linearly on the position of the incident laser spot. And the highest position sensitivity is 60 mV mm^{-1} over the displacement of the laser spot. These characteristics indicate the potential applications of the TiN/Si junction in photodetectors and position sensitive detectors.

1. Introduction

Intensive research on the photovoltaic properties of semiconductors has been pursued by many groups in the world due to their practical and wide applications in optoelectronic devices. Heterostructure photosensors based on silicon are attractive owing to their low cost, large photoresponse and easy compatibility with large-scale integrated circuit technology. High sensitivity and fast response are valuable qualities of photosensors. Chen and Chou have shown an Si-based metal–semiconductor–metal photodetector with a total grid area of $20 \times 26\,\mu m^2$ and they presented a high-speed response time of 5.4 ps [1]. Recently, Ismail *et al* also fabricated a high performance photodetector based on an Al-doped ZnO/n-Si heterojunction which showed a high responsivity of around 0.1 A W^{-1} and a high response speed in the nano-second order [2].

Titanium nitride (TiN) has become an important technological material due to its superior properties such as high melting point, low electrical resistivity, high surface hardness and good chemical stability [3–6]. Therefore, it is widely used as anti-corrosion and anti-wear coating [6]. The TiN film shows metallic property and can adhere to the Si substrate very well [7]. The TiN/Si junction has been studied by some groups [8–13]. Much work has been concentrated on the growth or electrical transport characteristics of the TiN/Si junction. However, as for as we know, no photoelectric property of the TiN/Si junction has been reported so far.

In this paper, we report on the photovoltaic effects observed in TiN/Si junctions in both vertical and lateral directions. The TiN/Si junction not only exhibited a high-sensitivity and high-speed photovoltaic response to laser illumination in the vertical direction but also presented a high position sensitivity over the displacement of the laser spot in the lateral direction.

2. Experiments

TiN films with a thickness of 100 nm were grown on p-type silicon substrates with a resistivity of 12.95 Ω cm by a laser molecular-beam epitaxy technique. Detailed growing procedures can be found in [14]. *In situ* reflection high-energy electron diffraction and *ex situ* x-ray diffraction confirmed that the TiN films were epitaxially grown on the Si substrate with good crystallized structures. The resistivity and mobility of the TiN films were 3.6×10^{-5} Ω cm and 583.0 cm^2 V^{-1} s^{-1}, respectively, by the Hall effect measurement [14].

The sample of TiN/Si was cut into 2×2 mm^2 and 10×8 mm^2 for vertical and lateral photovoltaic measurements, respectively. For I–V and vertical photovoltaic measurements,

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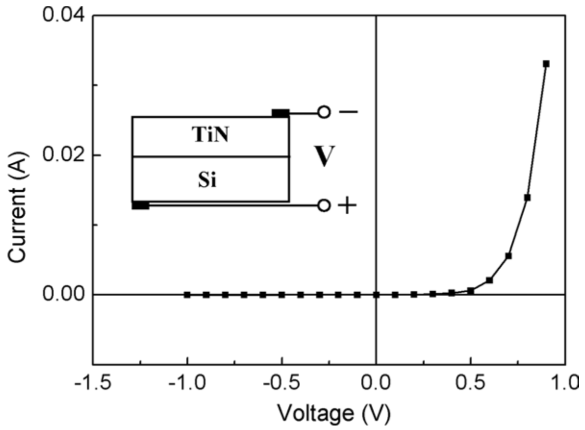

Figure 1. The I–V curve of the TiN/Si junction at room temperature in the dark. The top inset shows the schematic measurement circuit.

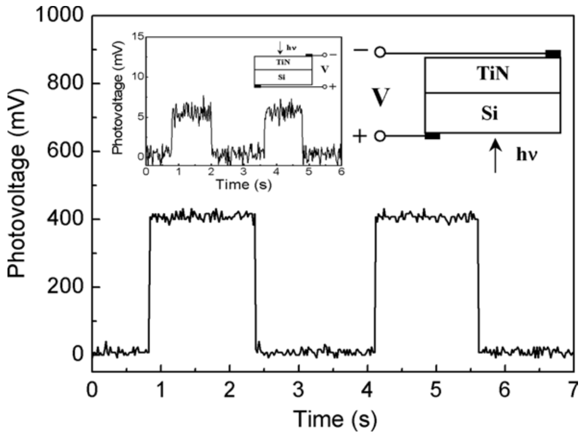

Figure 2. The steady vertical photovoltage under illumination of an HeNe laser incident upon the Si substrate. The upper left inset shows the vertical photovoltage under illumination of an HeNe laser incident upon the TiN film. The upper right inset shows the schematic measurement circuit.

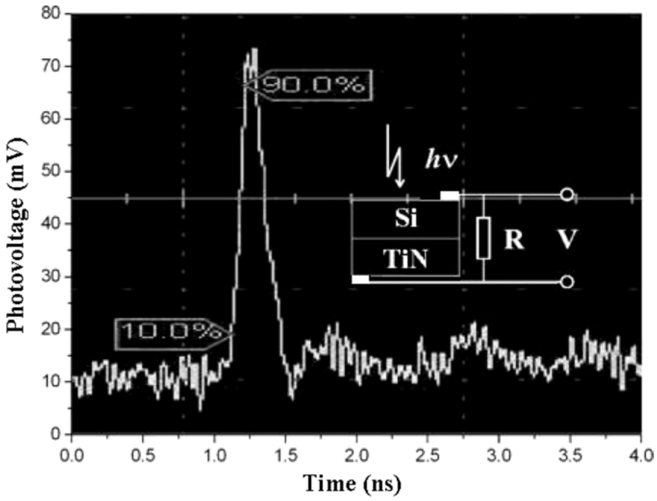

Figure 3. The time response of the TiN/Si junction under the excitation of a 25 ps laser pulse recorded by a 20 GHz digital oscilloscope. The inset shows the schematic measurement circuit.

two indium electrodes with a 0.5 mm diameter were placed on the surface corners of the TiN thin film and the Si substrate, respectively, as shown in the insets of figures 1–3. For lateral photovoltaic measurements, two indium electrodes separated by 8 mm were placed on the sample surface as shown in the insets of figures 4 and 5. The electrodes were always kept in the dark during measurements to prevent any electrical contact photovoltage. The photoelectric signals were recorded by a 20 GHz sampling oscilloscope. All the measurements in this paper were performed at ambient temperature.

3. Results and discussion

The current versus voltage characteristic of the TiN/Si junction was measured by a pulse-modulated current source. The measurement circuit is shown in the top inset of figure 1. The good rectifying property in the dark was observed as shown in figure 1. From the relation of the forward current versus voltage, the potential barrier height at the TiN/Si interface can be determined to be 0.58 eV, which is very close to that reported by Pelleg [13].

Figure 2 shows a vertical photovoltaic response of the TiN/Si junction under illumination of a 7 mW HeNe laser. The junction exhibited a large open-circuit photovoltage of 400 mV when the laser spot illuminated the Si side. However, when the laser illuminated the TiN film, only a photovoltage of ∼5 mV was observed as shown in the inset of figure 2 due to the extremely low transmission of the TiN film at the wavelength of 632.8 nm [15]. The vertical photovoltage across the p–n junction is caused by the separation of photogenerated electron–hole pairs spatially by the built-in field of the junction, which is the basic mechanism of a photovoltaic cell [16].

The time response of the vertical photovoltage of the TiN/Si junction was further investigated using a third harmonic of an actively–passively mode locked Nd : YAG laser with a wavelength of 355 nm and 25 ps pulse duration. To reduce the influence of the measurement circuit, a 0.2 Ω resistance was connected in parallel to the junction as shown in the inset of figure 3. Figure 3 shows a typical transient photovoltaic signal when the Si surface was irradiated. The rise time was 96 ps, and the full width at half maximum was 196 ps, which were faster than those observed in many other Schottky junctions based on Si [2, 17].

The lateral photovoltaic effect of the TiN/Si junction was also investigated. When the Si surface of the junction was partially illuminated by a laser spot, a large lateral photovoltage (LPV) was found between the two electrodes on the Si substrate. For LPV measurements, the position of the light spot on the sample surface in the x, y directions was determined by a high-precision x–y optical stage. As shown in the inset of figure 4(a), the lateral output voltage V_{DC} between the indium electrodes D ($x = 4$ mm, $y = 0$) and C ($x = -4$ mm, $y = 0$) on the Si surface was recorded by an oscilloscope with an input impedance of 1 MΩ.

Figure 4(a) shows the steady LPV V_{DC} dependence on the position of the laser spot (x, y). The HeNe laser spot with a diameter of 1 mm irradiated the Si surface. Each line in figure 4(a) denotes one scan of the laser spot with x from −3 to 3 mm and with y at a fixed value. We can see

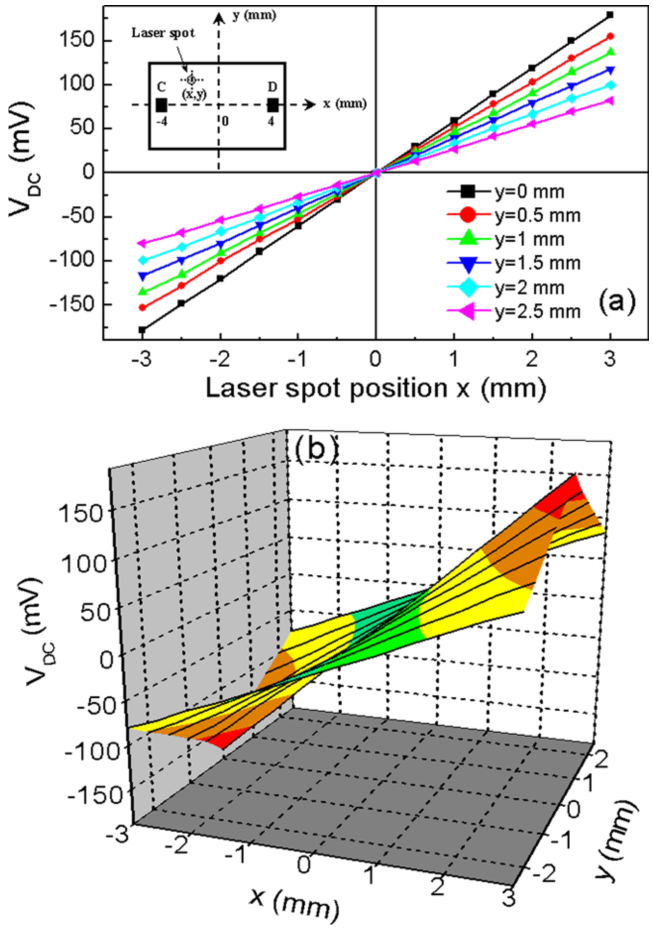

Figure 4. (*a*) Dependence of the LPV V_{DC} on the position of the laser spot position (x, y) on the Si surface under HeNe laser irradiation. The inset shows a layout of sample with contacts C (−4 mm, 0), D (4 mm, 0) and laser spot (x, y). (*b*) A three-dimensional plot of the LPV V_{DC} distribution with the position of the laser spot.

(This figure is in colour only in the electronic version)

that the lateral output voltage V_{DC} varied linearly with the laser spot position x. The voltage sign was reversed when the light spot was moved across the centre between the two contacts. When the light spot was at the centre, the voltage was zero. The position sensitivity, defined by the variation of the output voltage for 1 mm displacement of the light spot, was different for each scan. The highest position sensitivity was 60 mV mm^{-1} when $y = 0$ mm. To our knowledge, the sensitivity we have achieved is the highest sensitivity in large-area position sensitive detectors reported so far [18–28]. A three-dimensional distribution of the photovoltage V_{DC} in the plane of the junction was shown in figure 4(*b*). The LPV effect can be well explained by traditional LPV theory [29].

In order to exclude the possibility of the lateral photovoltaic effect originating from the In/Si/In structure, as a comparison, we also measured the LPV of the In/p-Si/In structure with the same In electrodes and Si wafer under the same experimental condition, but without the TiN thin film. Only 1–2 mV LPV was observed in the In/p-Si/In structure. So the much larger LPV V_{DC} in figure 4 must originate from the TiN/Si structure.

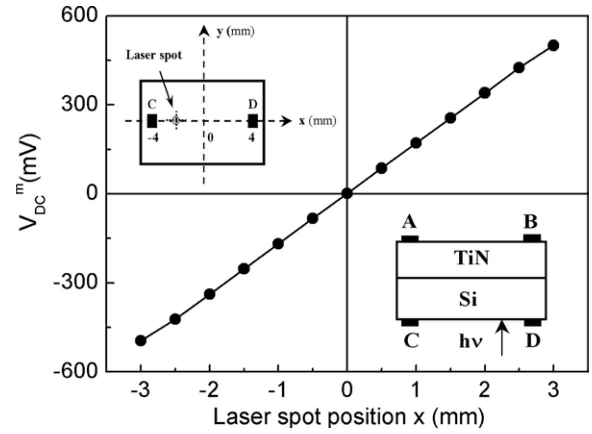

Figure 5. Dependence of the peak LPV V_{DC}^{m} on the position of the laser spot along the x direction ($y = 0$ mm) on the Si surface under the irradiation of a pulsed XeCl laser. The inset shows the schematic measurement circuit.

The LPV between electrodes A and B on the TiN film was always zero under illumination, because the TiN film with a low resistivity of 3.6×10^{-5} Ω cm and a high mobility of 583.0 cm^2 V^{-1} s^{-1} can be regarded as an equi-potential layer.

The transient LPV V_{DC} was also measured by a pulsed XeCl laser beam (energy density 0.1 mJ mm^{-2}, pulse width 20 ns) with a 0.5 mm^2 beam size. In response to the excitation of the pulsed laser, the photovoltage V_{DC} showed a pulse waveform with time. Here we denoted the peak value of the lateral voltage as V_{DC}^{m}. Similar to the steady LPV under HeNe laser illumination, the photovoltage V_{DC}^{m} also showed a linear relationship with the laser spot position x as shown in figure 5. The position sensitivity of the LPV V_{DC}^{m} to the displacement of the laser spot is 170 mV mm^{-1}, which is much larger than that in our previous transient results in the $La_{0.7}Sr_{0.3}MnO_3$/Si and $La_{0.9}Sr_{0.1}MnO_3$/$SrNb_{0.01}Ti_{0.99}O_3$ heterojunctions [30,31]. As mentioned in our previous report [31], the mechanism of the transient LPV effect for higher light power density is different from traditional LPV theory. The Dember effect and the interface effect play an important role in the transient LPV [31,32].

4. Conclusion

In conclusion, we have presented the ultrafast and high sensitivity photovoltaic effects in TiN/Si Schottky junctions. The open-circuit vertical photovoltage across the junction is 400 mV under the illumination of an HeNe laser with a power of 7 mW. The LPV exhibits a linear dependence on the position of the laser spot, and the highest position sensitivity can reach 60 mV mm^{-1}. The high sensitivity and fast response speed (∼ps order) make the TiN/Si junction promising for wide applications, such as in photodetection or position sensitive detection. Considering the excellent chemical stability and good mechanical properties (hardness and elasticity) of the TiN film, the detectors based on the TiN/Si junction can be used in some rigorous environments.

Acknowledgments

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