Characteristics of Visible-Blind p-Cu_2O/n-Si Heterojunction Fabricated by Plasma-Induced Bonding Technique

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Abstract

The fabrication and characterization of the Cu_2O-Si heterojunction produced by plasma-induced bonding technique were presented in this work. The produced heterojunction was asymmetrical consisting of p-type Cu_2O on a n-type silicon substrate. The built-in potential of this heterojunction was determined to be about 0.75 eV with typical spectral responsivity within the range 200-400 nm and maximum responsivity at 350nm. With dark current of 37 μA, maximum reverse bias current of 165 μA and ideality factor of 1.22, the results explained better characteristics than those of the same heterojunction produced by some other techniques. The main advantages of this visible-blind heterojunction are the low cost and high responsivity.

Keywords: heterojunctions; Copper oxide; Silicon devices; Electrical characteristics; Plasma-induced bonding
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1. Introduction

Several other high potential applications of bonding have emerged in microelectromechanical systems (MEMS) and as a way of integrating dissimilar crystalline materials despite that the main driving force for development of bonding has been production of silicon-on-insulator (SOI). To reach a sufficient level of maturity, bonding procedures need to be optimized and standardized according to the application. Also, bonding requires a high-temperature annealing step after the room temperature joining, to ensure the formation of a strong and uniform bonding. This high temperature annealing is sometimes incompatible with many applications and, in some case, it may cause material degradation, especially when bonding thermally mismatched materials [1-4].

The plasma affects a surface mainly in two ways: physically and chemically. Physical plasma/surface interaction is due to bombardment of energetic ions [5]. The bombarding ions would cause sputtering, mixing and defect formation. Chemical interaction is driven by chemically active species in the plasma [6]. Plasma is a partially ionized gas with equal number of positive and negative charges. At steady state, the free electrons acquire sufficient energy from the applied electric field to produce impact ionization of the gas, at a rate equal to the loss rate [7]. Since the electrons are more mobile due to their lower masses, they diffuse faster to the surrounding surfaces, including substrate surface and chamber wall. This builds up a negative potential at the surrounding surfaces, while the plasma is ‘depleted’ from negative charges. Therefore, the plasma potential is always positive [8,9]. A body immersed into plasma hence acquires a negative floating potential. The ions in the plasma are accelerated through the plasma sheath and bombard the surrounding surfaces. However, by applying an external field, the energy of the ions bombarding the substrate can be adjusted. Many capacitive discharges are asymmetric, because the RF-driven electrode area is smaller than the grounded area, which is usually the chamber wall. This causes the driven electrode to acquire a self-bias dc offset voltage [10-14].

In this work, asymmetrical Cu_2O-Si heterojunctions are produced by plasma-induced bonding technique and their spectral and electrical characteristics are enhanced when compared to similar heterojunctions produced by other techniques.

2. Experimental Part

High purity (99.999) (111)-oriented n-type silicon wafers of 500 μm thickness and 3 Ω.cm resistivity were used in this work. Also, high purity (99.999) copper oxide (Cu_2O) was used to form 350 μm-thick samples. Both samples, Si and Cu_2O, were washed with distilled water then rinsed in ethanol and subjected to ultrasonic waves for 10 minutes, then dried by hot air. The silicon samples were then cleaned with HF for 5 minutes to remove any residual oxides which have existed on their surfaces. Both samples were softly grinded and polished to obtain flat surfaces. Then, these samples were rinsed in ethanol to remove acids then dried to be ready for processing.

The Si and Cu_2O samples were mounted inside the homemade plasma system, which is working under vacuum of 10^{-4} mbar at room temperature. The samples were placed at a position that the plasma is entirely surrounding the sample. Discharge voltage and current are 15 kV_{DC} and 3A, respectively. Argon gas at a pressure of 1 mbar was used to generate the discharge plasma. The sample was maintained inside the operated system for 10 minutes before being removed and tested.

Before bonding, the native oxide is removed from the surfaces to have a solid-to-solid bonding. However, the bonding is very weak at room temperature and after low-temperature annealing because of the hydrogen-terminated surface [17]. A high-temperature annealing above 520°C is necessary to desorb hydrogen from surface and enable a covalent bonding.

The difference in thermal expansion between Cu_2O and Si will induce high mechanical stress in the material when annealing the bonded samples at high-temperatures. The thermal stress degrades the material by generating defects. It can also cause cracks and completely debond. The main degradation occurs in Cu_2O since Si is mechanically stronger.

Electrical measurements were carried out using a Farnel DC power supply and Keithley-616 digital electrometer while the C-V measurements were performed using hp/4192 ALF LCZ device. The samples were subjected heating up to 600°C within 5 minutes then left to return to its initial temperature within the same period of time.

3. Results and Discussion

Figure (1) shows the I-V characteristics of bonded p- Cu_2O/n-Si heterojunction. As shown, the dark current is about 37 μA and the forward current is uniformly linear. The illumination current in the reverse biasing reaches a maximum of about 165 μA. The bonded interface is often avoided in the electrically active region of the electronic device. However, the recombination centers of the defective bonded interface are used to control the minority carrier lifetime in power devices. These characteristics are typically enhanced compared to results obtained by other techniques [18,19] and table (1) shows a comparison among the parameters of three different techniques (thermal evaporation, dc sputtering and plasma bonding).

Table (1) Electrical parameters of the Cu_2O/Si heterojunction prepared by different techniques

Technique	Id (μA)	$I_{rmax.}$ (μA)	V_{bi} (eV)	IF
TE	80	140	1.2	0.6
DCS	65	110	0.8	0.82
ALD	20	70	0.6	1.6
PIB	16.5	60	0.75	1.22

TE: thermal evaporation; DCS: dc sputtering; ALD: atomic layer deposition; PIB: plasma-induced bonding; I_d: dark current; I_{rmax}: Maximum reverse current; V_{bi}: built-in potential; IF: ideality factor

In order to introduce the nature of the asymmetrical Cu_2O-Si heterojunction, the C-V measurements were performed in the reverse biasing and results are presented in Fig. (2). The built-in potential was determined for the Cu_2O-Si heterojunction to be about 0.75eV.

Integration of Cu_2O and Si has attracted much interest since the unique properties in each material can be combined in devices or systems, such as Cu_2O-based piezoelectric devices and optoelectronics components.

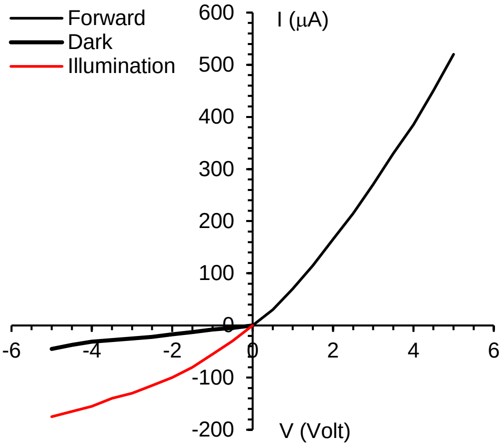

Fig. (1) The I-V characteristics in dark and light for the Cu_2O-Si heterojunction prepared in this work

The epitaxial growth of Cu_2O on Si substrate is hampered by the difference between the lattice constants of the materials. However, using bonding for the integration, the lattice-mismatch becomes no obstacle. Unfortunately, there is a large difference in thermal expansion between Cu_2O and Si. When bonding solids of dissimilar materials and annealing at elevated temperatures, the thermal mismatch will induce high thermal stress in the material [20].

For lattice-matched materials systems, the material integration is extensively and routinely realized using heteroepitaxy. However, for material systems that are largely lattice-mismatched, heteroepitaxial growth has not been able to produce the high quality material needed in optoelectronics [21-22]. Heteroepitaxial growth of Cu_2O on Si has been a subject of interest and although improvement is continuing, the densities of threading dislocations in Cu_2O seem to have saturated at more than ten thousand times higher than the value for lattice-matched epitaxy on Cu_2O. The dislocation density and material quality have been improved by indirect growth of Cu_2O on Si using SiO_2 intermediate buffer layers or various epitaxial layer overgrowth (ELO) and conventional growth techniques. The principal feature in ELO is that growth proceeds laterally over a cap-layer, which inhibits transmission of threading dislocation.

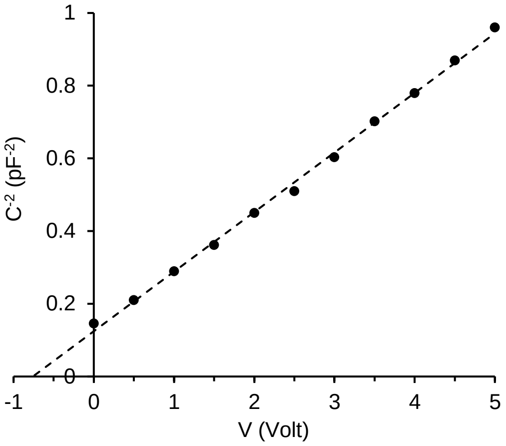

Fig. (2) The C-V characteristics of the Cu_2O-Si heterojunction prepared in this work. The value of V_{bi} is about 0.75 eV

The spectral responsivity of the Cu_2O-Si heterojunction was determined as a function of wavelength as shown in Fig. (3). This heterojunction responds in the 200-400 nm range much more than in the wavelength range longer than 400 and the maximum responsivity is measured at 350 nm. The responsivity was increased from 0.065 A/W at 200 nm to 0.9 A/W at 350 nm while sharply dropped to lower than 0.1 A/W at 380 nm. This heterojunction can be considered as blind to the wavelengths longer than 400 nm (visible and infrared). This low-cost technique presents an advantage to produce good photodetectors for a wavelength region centered at 350nm.

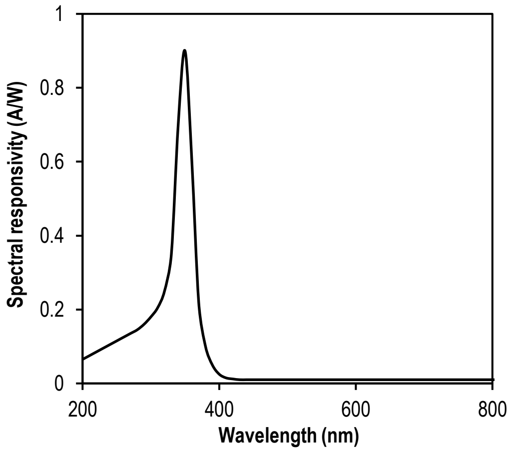

Fig. (3) The spectral responsivity of the Cu_2O-Si heterojunction

4. Conclusion

An asymmetrical Cu_2O-Si heterojunction was produced by plasma-induced bonding technique. The electrical measurements showed reasonable enhancement in the heterojunction characteristics compared to that produced by other techniques. Despite the complexity imposed by the plasma processing system, production of heterojunctions with such enhanced characteristics has advantages of low cost and large size devices. The produced heterojunction exhibited dark current of 37 μA, maximum reverse bias current of 165 μA, built-in potential of about 0.75 eV, ideality factor of 1.22, typical spectral responsivity within the range 200-400 nm and maximized at 350 nm.

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