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A study of ageing effect at elevated temperature of flexible silicon diodes integrated using conductive adhesives

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ABSTRACT

A simple fabrication scheme of using silver-filled conductive tape to form flexible single crystalline Si–Pd Schottky diodes on a polymer substrate has been studied and reported previously. In this investigation, we studied the long term thermal stability of these flexible diodes on polymer annealed at 80 °C in open air for 1 year. The *I–V* characteristics of the diodes were measured periodically. We found that the barrier height of the Si–Pd diodes remained relatively unchanged at 0.795 eV ± 0.003 with an *n*-factor of 1.03 ± 0.03, and a series resistance of ~110 Ω for diodes with a 950 μm diameter, which are almost identical to the values before annealing. The integrated structure stayed flexible to a similar curvature after 1 year. The stability of silver-filled conductive tape was investigated separately over the same period of time and under the same conditions. The resistance of two conductive tapes was found to quickly decrease from high initial values to significantly lower values, and remained constant over the course of the investigation. Based on these results, we conclude that this simple bonding technique of using conductive tape to fabricate flexible devices can be of useful value in practical applications.
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1. Introduction

Recent advancements have been made in developing an array of flexible electronic devices that can be incorporated into clothing, worn on the person, or built into the canvas of a camping tent [1–3]. The potential to wear a cellphone or medical device that conforms to your body is certainly exciting. The devices currently being developed typically rely on traditional fabrication techniques that are labor intensive and expensive. We have developed and investigated a technique that aims to simplify fabrication and is likely to lower the cost of production by replacing traditional metal bonding with a conductive adhesive. It is our objective that the results reported in this study would be useful to improve the field of wearable electronics.

In a previous proof of concept investigation [4], we reported a simple fabrication technique of making flexible Si–Pd diodes on a polymer substrate. In this technique, we used a simple backside bonding agent: electrically-conductive silver colloid-filled adhesives in the form of double-sided tape or epoxy. These adhesives are readily integrated into low-temperature bonding processes compatible with polymer substrates, and exhibit excellent flexibility. To investigate their utility, these adhesives were used in the bonding process of flexible single-crystal Si–Pd Schottky diodes with polymer substrates. The electronic properties of the as-fabricated diodes are briefly summarized in Table 1.

In this publication we report our study of the stability of four properties:

(1) Structural stability – the entire integrated structure, from the flexible substrate (PEN) to the top Pd metallization on top of thin Si.
(2) Interfacial stability – interface between the PEN and the Ag tape, as well as that between the Ag tape and the Si backside contact.
(3) Electronic stability – the stability of the electronic properties of the Schottky diodes integrated on the composite structure.
(4) Stability of the Ag tape – adhesion and total electrical resistance.

2. Experimental method

A commercially available 5-in.-diameter 30 μm-thick n-Si ⟨100⟩ wafer was used for this study. Hall-effect and 4-point-probe measurements of the wafer indicated a carrier density (N_d) of $5.6 \times 10^{14}\ \mathrm{cm}^{-3}$. Eighty nanometers of titanium followed by 240 nm of gold were evaporated on the backside and annealed at 450 °C under forming gas for 10 min to form an Ohmic contact.

The samples were then affixed to a sapphire handle wafer with an adhesive layer of Shipley S1818 photoresist to facilitate handling. After this temporary bonding, a 150 nm palladium film was evaporated on the front side as the Schottky metal and

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Table 1
As-fabricated device properties. Barrier height (Φ_B), ideality factor (η), and series resistance (R_S).

Φ_B	0.77 eV (σ = 0.003 eV)
η	1.02 (σ = 0.01)
R_S	82 Ω (σ = 36 Ω)

950 μm-diameter circular dot masks were patterned on the front with photoresist.

The surrounding Pd was etched with diluted *aqua regia* (3:2:1 HCl:HNO_3:H_2O, 40 s, room temperature), and 3 μm silicon isolation mesa was formed with *CP-4* (2:5:5 HF:HNO_3:CH_3COOH, 10 s, room temperature) etching to reduce edge leakage current. Following device processing, the completed diodes were carefully debonded from the sapphire handle with an overnight soak in acetone and re-bonded to a polyethylene naphthalate (PEN) substrate with double-sided silver tape (Nisshin em Co., Ltd.). The initial tape thickness and resistivity were 170 μm and 8 mΩ cm, respectively. The as-fabricated device structure is shown in Fig. 1a. A top side view of the diodes is seen in Fig. 1b. The flexibility of the diode structure is demonstrated in Fig. 2.

The current–voltage (*I–V*) characteristics were analyzed using the thermionic model of Schottky diodes [5]. From the exponential fit of the data under forward bias (Fig. 3a), the ideality factor (*n-factor*) of the diode was determined to be 1.02 (standard deviation σ = 0.01). The value is well within the accepted upper bound of 1.1 for which the metal–semiconductor barrier height can be reliably extracted [6]. The extracted barrier height Φ_B was 0.770 eV (σ = 0.003 eV), is consistent with the literature for Pd–nSi systems [7–9]. The average series resistance of the tape-bonded diode was determined to be 82 Ω (σ = 36 Ω). The properties for the as-fabricated diodes are summarized in Table 1. No significant difference was found in the *I–V* behavior of a separate but very similar diode set from the same wafer before and after integration with plastic substrates (data not shown here). Capacitance–voltage measurements were in agreement with barrier height results to within 3.2%. A reverse bias of up to −100 V was applied (the limit of the test equipment) with no sign of breakdown (Fig. 3b). These results have been reported in the literature [4] and in Table 1.

3. Experimental results and discussion

The behavior of the diodes after an extended period of time at elevated temperature can be useful in estimating long-term reliability [10]. The original use of a silver-filled adhesive, as a means to provide a less processing-intensive alternative to metal bonds, left questions as to how these devices would perform over a long period of time at an elevated temperature. These diodes were placed onto a hotplate at 80 °C in open air. Weekly measurements of the current–voltage (*I–V*) characteristics were analyzed using the thermionic model of Schottky diodes for the period of 1 year. The humidity in the lab ranged from 55% to 75% over the course of the year. Each week 3 out of 10 diodes on a device were chosen for measurement. The values for *n*-factor, barrier height, and series resistance were extrapolated from their current–voltage curve and the average was reported.

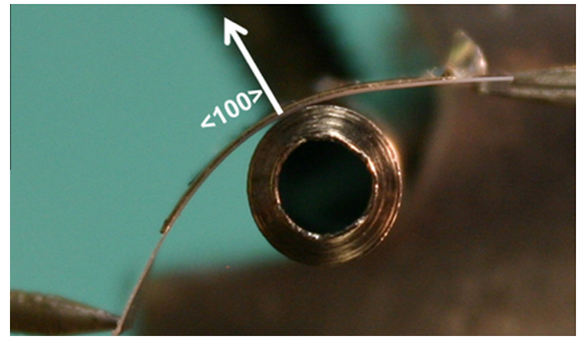

Fig. 2. Side-view of thin Schottky diode being flexed. The sample is centered over a fixed horizontal rod. One end of the sample is immobilized while the other end was bent downward via a needle attached to a micromanipulator. The crystal orientation of the substrate is shown for reference. Reprinted with permission from Appl. Phys. Lett. 100, 072103 (2012). Copyright 2012 American Institute of Physics.

It was found that each property under investigation remained unaffected at 80 °C. Accelerated annealing tests were done at 120 °C, 150 °C, and 180 °C with the temperature held constant for two weeks between steps. The results of the accelerated experiments showed that the flexible substrate, PEN, became brittle and was no longer viable as a flexible carrier at temperatures higher than 80 °C. All other properties remained unaffected.

The post-annealing *I–V* behavior and reverse behavior of up to −100 V are shown in Fig. 4a and b respectively. In Fig. 4a we see no significant change in the linear thermionic region after 1 year of annealing at 80 °C in open air, however the slope of the ohmic region can be seen to decrease the longer the period of annealing. Fig. 4b shows that the breakdown voltage is consistent with the pre-annealing behavior of the diode shown in Fig. 5b.

Fig. 5 shows the average calculated *n*-factor of three 950 μm diodes over the period of 1 year. The averaged *n*-factor remained constant at 1.03 (standard deviation σ = 0.03) for the entire year. Compared to the original value of 1.02 the *n*-factor changed only slightly after a year of heating. The *n*-factor is found from the slope of the linear region on a semilog plot of a diode's *I–V* behavior. The decades of linearity of an *I–V* curve provide insight into the interfacial stability because the number of decades is directly related to the junction resistance between the metallization and the silicon. In the linear region of the plot the junction resistance dominates the negligible series resistance of the device. As voltage across a device increases the series resistance approaches a similar

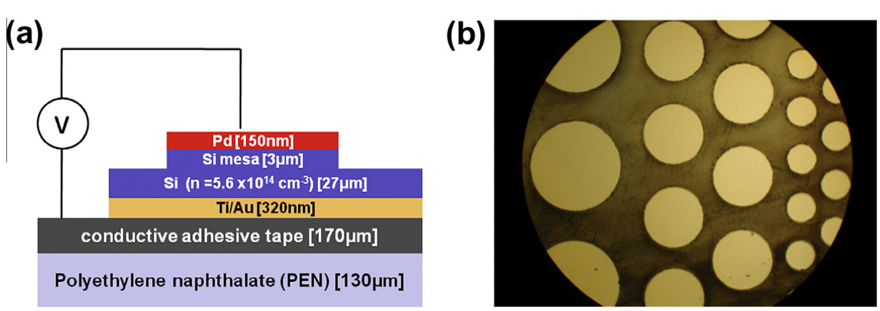

Fig. 1. (a) Side-view structure of flexible thin Si–Pd Schottky diode. Reprinted with permission from Appl. Phys. Lett. 100, 072103 (2012). Copyright 2012 American Institute of Physics. (b) Optical microscope image of the top-view of the Si–Pd Schottky diodes. Only the largest diodes, 950 μm diameter, are reported.

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