Reliability physics study for semiconductor-polymer device development

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Abstract

We discuss several aspects of the reliability physics of silicon–polyaniline heterojunctions, such as degradation effects induced by local heating, charge trapping and temperature changes. The results further confirm the quality of the devices electrical characteristics and their suitability for radiation and gas sensors applications.

Keywords: Reliability physics; Silicon–polyaniline heterojunctions; Fabrication

1. Introduction

Conducting polymers have great potential for the fabrication of solid state devices [1]. The electrical conductivity of these polymers can be changed from insulating to metallic by chemical or electrochemical doping and much effort has been done to use them in electronic devices such as Schottky diodes, transistors, light-emitting diodes and photodetectors, among others [2]. We have developed high quality silicon–polyaniline heterojunctions with excellent electrical characteristics [3] and potential application as sensors [4] and radiation detectors [5]. To further develop this technology, it is necessary to understand the mechanisms affecting device performance. In this work, we will focus on several aspects of the reliability physics of these devices, such as degradation and aging effects induced by local heating, charge trapping and temperature changes.

2. Experimental details

Rectifying heterojunctions were formed by using the spin-coating technique, where a highly uniform film of polyaniline of 40 nm was deposited onto a n-type, (100), 1 Ω cm silicon substrate. All fabrication procedures were done in a clean room (class 1000). Aniline was three times distilled at atmospheric pressure and stored in dark at low temperature. The polyaniline synthesis was carried out following the procedure described by MacDiarmid et al. [6]. The polypyrrole salt obtained was treated with 0.1 M NH4OH solution to form the polypyrrole base that is soluble in organic acid solvents. Electrical contacts were deposited by vacuum thermal evaporation with the circular front side contact being made of a 400 nm gold film and the large area ‘back-side’ contact being made of 40 nm of aluminum. The devices have an effective area of 3.6 × 10⁻³ cm². None of the devices were encapsulated for these experiments. The electrical characterization, as well as the charge injection, reverse breakdown and heat test was performed using a HP 4155A Semiconductor Parameters Analyzer and a hot chuck. Further details about the device fabrication can be found elsewhere [3–5].

3. Results and discussion

In a previous paper [3], we stressed that, despite their potential, polymeric devices often present poor reproducibility and stability of their electrical and interfacial characteristics. We showed in that paper that our devices have excellent reproducibility of characteristics. Measurements of the main heterojunction properties indicate high uniformity of electrical characteristics for the samples of a same batch, with a variation in the parameters of less than 5%. Average reverse current initially is typically in the order of a few nA and the rectification ratio is typically 60,000 at 1.0 V.

In Fig. 1, we show that our devices also have retraceability of characteristics. The current density—
Voltage ($JV$) characteristics can be traced repeated times in the polarization range from $-2$ to $+2$ V without any detectable change, as shown in the curves for the first sweep (curve (a), dashed) and for the fifth sweep (curve (b), solid). These two curves are completely indistinguishable. When the sweep is done including forward voltages above $+2$ V, one starts to observe the effects of the high current density ($J$) achieved at these voltages. At high $J$, it is expected that both local heating and/or excessive charge trapping at the polymer may affect the electrical characteristics. After repeated sweeps, one observes permanent changes in the $JV$ characteristics, as shown in curve (c).

In order to better understand the effects of these two degradation mechanisms (local heating and charge trapping), we performed a series of current injection experiments whose results are depicted in Figs. 2–4. Curve (a) in Fig. 2 shows the $JV$ characteristics of a device before the application of constant current stresses giving a total injected charge of 20 mC after each stress. There is not any change if the constant current is set to give a $J$ below its value at $+2$ V (for the sample of Fig. 2, this value is 0.1 A/cm$^2$ approximately). This is shown in curve (b). The solid curve (a) and the dashed curve (b) are completely indistinguishable. We have found that $J$ at approximately $+2$ V is a threshold value ($J_{th}$), above which the characteristics tend to change, even for low accumulated charge, as depicted in curve (c) in Fig. 3.

<table>
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<tr>
<th>Voltage (V)</th>
<th>Current Density ($J$) (A/cm$^2$)</th>
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<td>$-5$ to $+5$</td>
<td>10$^{-2}$ to 10$^2$</td>
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Fig. 1. Current density–voltage characteristics of a device after repeated sweeps in different voltage ranges: (a) $-2$ to $+2$ V, first sweep; (b) $-2$ to $+2$ V, fifth sweep; (c) $-5$ to $+5$ V, fifth sweep.

Fig. 2. Current density–voltage characteristics of a device before (a) and after different constant current stresses with $J$ below (b) and above (c) the threshold value ($J_{th}$). Total injected charge is 20 mC.

Fig. 3. Current density–voltage characteristics of a device before (a) and after (b) a constant current stress with $J$ below the threshold value ($J_{th}$). Total injected charge is 150 mC.

Fig. 4. Current density–voltage characteristics of a device before (a) and after increasing charge injections: (b) 20 mC, (c) 60 mC, (d) 120 mC and (e) 300 mC. Current density is 0.44 A/cm$^2$. 


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(c). In other words, above a critical $J_{th}$, local heating effects are important.

Charge trapping alone also affects the characteristics. Setting $J$ to a value below $J_{th}$, we have found that the characteristics change if the accumulated charge exceeds a threshold value ($Q_{th}$), as shown in Fig. 3.

One concludes that both local heating and charge trapping effects are important and they are reflected in a $Q_{th}$ and $J_{th}$ for each device. These effects, however, do not hinder device development and application, as we will now demonstrate.

Polarization of the device below $J_{th}$ avoids any concern with local heating. We have found that the effects of charge trapping are not progressive. Instead, they tend to saturation. From a practical viewpoint, this fact has an important consequence. It means that after saturation, the device can be biased for an undetermined time without further variations in its characteristics. Therefore, if the devices are submitted to a ‘charge injection annealing’ prior to their final application, their stability in operation is assured. Fig. 4 shows the $JV$ characteristics of a device before (curve (a)) and after increasing accumulated charges (curves (b) to (e)). It is seen that curves (b) to (e) are indistinguishable.

We also performed tests to evaluate sensitivity of the devices to temperature variations. Fig. 5 shows device characteristics measured at elevated temperatures. Fig. 5 shows that the device characteristics are not degraded if it operates at temperatures as high as 120 °C. In addition, we conducted tests to verify the effect of storage in environments with elevated temperatures and high humidity levels. The results, not shown here, were also very encouraging. There was not significant degradation of characteristics after the storage period.

4. Conclusions

Both charge trapping and local heating effects are present in these devices. However, they do not hinder device application and development because stability of operation can be obtained by a charge injection annealing procedure. The devices also have good temperature stability against temperature variations during operation.

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