Hybrid Amorphous/Nanocrystalline Silicon Schottky Diodes for High Frequency Rectification

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***Abstract*— We report hybrid amorphous (a-Si)/nanocrystalline (nc-Si) Schottky diodes for rectification at high frequencies. All fabrication steps are done at <200 °C, making them compatible with processing on plastic. The diodes have a high current density (5 A/cm^2 at 1 V and 100 A/cm^2 at 2 V) and ON-to-OFF current ratio (over 1000 for bias voltages of 1/−8 V). A 0.01-mm^2 hybrid diode has a series resistance of 200 Ω and a capacitance of 7 pF, leading to a cutoff frequency of 110 MHz. As a half-wave rectifier driving a parallel 1-MΩ resistive and 100-nF capacitive load, the dc rectified voltage drops at frequencies >10 MHz, with a −3 dB point at 70 MHz.**

***Index Terms*— Schottky diode, rectifier, half-wave, nanocrystalline silicon (nc-Si), amorphous silicon (a-Si), high frequency, power conversion efficiency.**

I. INTRODUCTION

THIN-FILM rectifiers, compatible with processing on plastic substrates, are key components for large-area electronic systems. One of the principal motivating applications are RFID tags, which have been fabricated with both organic [1] and metal oxide rectifiers [2]. The tag relies on a rectifier to convert a high frequency signal, often received through an inductive antenna, to DC. Another application involves sensing systems, based on large-area sheets of thin-film electronics and ICs [3]. Chip-on-flex ICs communicate with laminated large-area sheets via noncontact near-field inductive links; once an AC signal is received by the sheet it must be converted to DC. In these applications the inductive links function best at high frequencies, highlighting the need for thin-film diodes for AC-to-DC rectification at high frequencies.

In this letter we present a hybrid amorphous silicon (a-Si)/nanocrystalline (nc-Si) silicon Schottky diode, fabricated at 180 °C, making it compatible with processing on plastic. Also, it is grown using standard a-Si plasma-enhanced chemical vapor deposition (PECVD) equipment and requires no p-type doping, allowing for the possibility of manufacturing via a conventional a-Si TFT fabrication line used for AMLCDs. Schottky diodes made entirely out of a-Si, such as those we previously reported [4], had a cutoff frequency less than 5 MHz. The hybrid diode overcomes this frequency limitation with a cutoff frequency of 110 MHz.

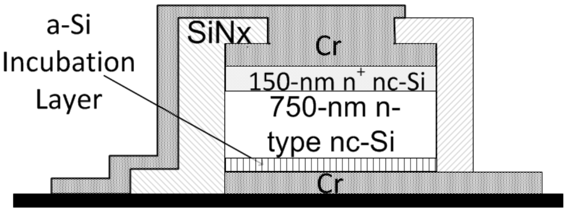

Fig. 1. Device structure of hybrid a-Si/nc-Si Schottky diode.

II. DEVICE FABRICATION

The structure of the hybrid diode, shown in Fig. 1, consists of a chromium (Cr) Schottky contact at the bottom, 750-nm n-type nc-Si, 150-nm n$^+$ nc-Si, and a Cr ohmic contact on top. The nc-Si is grown using PECVD at 180 °C, with a very high frequency (VHF) excitation of 70 MHz, 500 mTorr pressure and a power density of 120 mW/cm^2. The n-type nc-Si is grown with a gas ratio of SiH_4/H_2 = 4/100 sccm and the n$^+$ nc-Si with $SiH_4/H_2/PH_3$ = 4/120/0.2 sccm. The lightly doped nc-Si is not explicitly doped, but, likely due to oxygen impurities [5], has a donor density of 10^{16} cm^{-3}, as found from C-V measurements [Fig. 3(a)]. The layer initially grows as a-Si before the nc-Si nucleates; thus, the Schottky interface of the lower contact is probably between the Cr and the thin a-Si incubation layer. The device is encapsulated using 200-nm PECVD silicon nitride.

III. RESULTS AND DISCUSSION

A. DC Characteristics

The hybrid diodes have a current density of 5 A/cm^2 at 1 V and 100 A/cm^2 at 2 V [Fig. 2(a)], which is $\sim 10^4$ times greater than a Schottky diode formed entirely of a-Si [4]. This also compares favorably with other diodes deposited with PECVD, including p-i-n a-Si ($\sim 10^{-3}$ A/cm^2 at 1 V) [6] and nc-Si Schottky diodes ($\sim$0.1 A/cm^2 at 1 V) [7]. The current density

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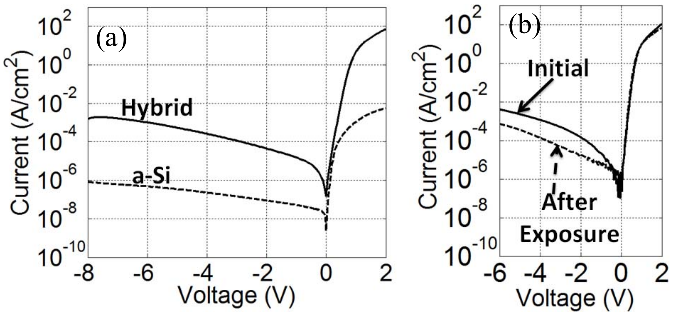

Fig. 2. (a) J-V characteristics of the hybrid and an entirely a-Si Schottky diode. (b) Effect of being exposed to ambient conditions for 20 days.

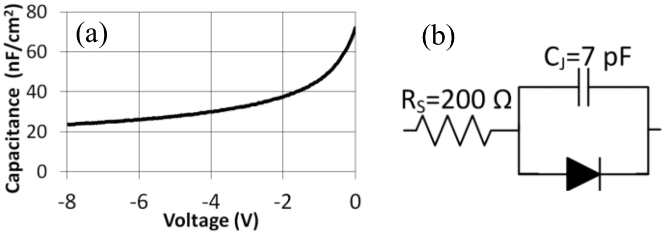

Fig. 3. (a) C-V curve of the hybrid diode, measured at 1MHz. (b) Circuit model of 0.01 mm^2 hybrid diode.

of the hybrid diode can be attributed to the high conductivity of the nc-Si, which means that unlike Schottky diodes formed entirely out of a-Si, they are not affected by a space-charge-limited current regime. The hybrid diodes are also stable in air, so their J-V characteristics do not degrade considerably when exposed to the environment for 20 days [Fig. 2(b)].

B. AC Characteristics

The C-V curve of the hybrid diode, measured at 1 MHz, is shown in Fig. 3(a), with a 0 V bias capacitance (C_J) of 7 pF for a 0.01 mm^2 diode. The circuit model for this diode [Fig. 3(b)] has a series resistance (R_S) of 200 Ω extracted from the J-V curve [Fig. 2(a)]. This leads to a cutoff frequency ($f_c = 1/2\pi R_S C_J$) [8] of 110 MHz.

Our goal is to use the diodes as rectifiers for AC-to-DC voltage conversion at high frequencies. To evaluate their performance we built a half-wave rectifier and measured the DC output voltage (V_{out_DC}), while varying the frequency of an input voltage source (V_{in}) with a 4 V peak amplitude [Fig. 4(a)]. The load resistance consisted of a parallel 1 MΩ resistive and 100 nF capacitive load, which together serve as a low-pass filter and DC load. A 50Ω resistor to ground was used at the input for transmission-line termination. In the experimental setup, shown in Fig. 4(b), surface mount components were directly connected to the glass substrate on which the diode was fabricated. Fig. 4(c) shows the output waveform at 10 MHz and Fig. 4(d) at 100 MHz, respectively. Fig. 4(e) shows that between 1 kHz and 10 MHz V_{out_DC} is constant at 3.3 V. At frequencies greater than 10 MHz V_{out_DC} starts to drop with a −3 dB point at 70 MHz. A SPICE simulation of the circuit, represented with the solid line, satisfactorily fits the experimental data.

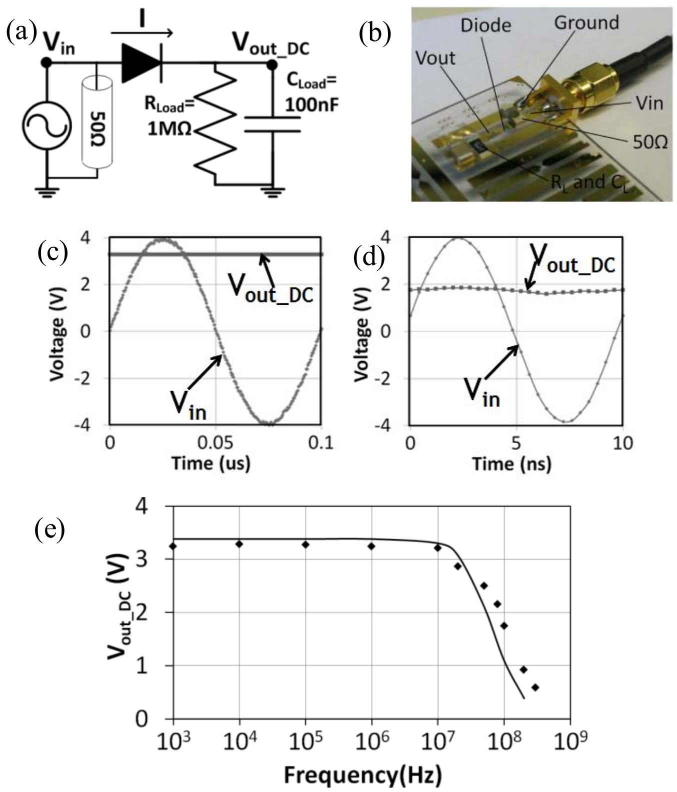

Fig. 4. AC-to-DC rectification with a half-wave rectifier. (a) Half-wave rectifier circuit. (b) Experimental setup. (c) Waveforms from oscilloscope at 10 MHz. (d) Waveforms from oscilloscope at 100 MHz. (e). Output DC voltage (V_{out_DC}) as a function of input (V_{in}) frequency, with a 4 V amplitude. Diamond points are experimental data and curves are SPICE simulations.

Beyond the ability to rectify signals to DC, a key metric is AC-to-DC power conversion efficiency for an inductive link. This efficiency will have an upper limit set by the power conversion efficiency of the diode, given by $\eta = P_{Load}/P_{Supply}$, where P_{load} is the power delivered to the load (R_{load}) and P_{supply} is the total power provided by the voltage source. To carry out this measurement we continued to use the half-wave rectifier circuit, shown in Fig. 4(a), tested with both a 1 kΩ and 1 MΩ resistive load, and a parallel 100 nF capacitive load. P_{load} is given by $P_{Load} = V^2_{out\_DC}/R_L$ and $P_{Supply} = \frac{1}{T}\int_0^T I(t)V_{in}(t)dt$ where T is the period of the source. Fig. 5(a) shows how for a 1 MΩ load resistor P_{Load} remains approximately constant at ∼9 μW from 1 kHz to 20MHz, but drops above 20 MHz due to V_{out_DC} diminishing, as depicted in Fig. 4(e). P_{Supply} is constant at ∼14 μW from 1 kHz to 100 kHz, but increases at higher frequencies beginning just below 1 MHz. This is because at higher frequencies there is more current through the diode capacitance C_J [Fig. 3(b)] and load capacitor C_{Load}. This leads to more current and correspondingly more power loss through the diode series resistance R_S, reflected by an increasing P_{supply}. Thus, the power efficiency for a 1 MΩ load resistor [Fig. 5(c)] is constant at ∼70% at low frequencies, and drops rapidly above 100 kHz. Fig. 5(b) shows how for a 1 kΩ load resistor P_{Load} remains approximately constant from 10 kHz to 10 MHz and drops at higher frequencies, while

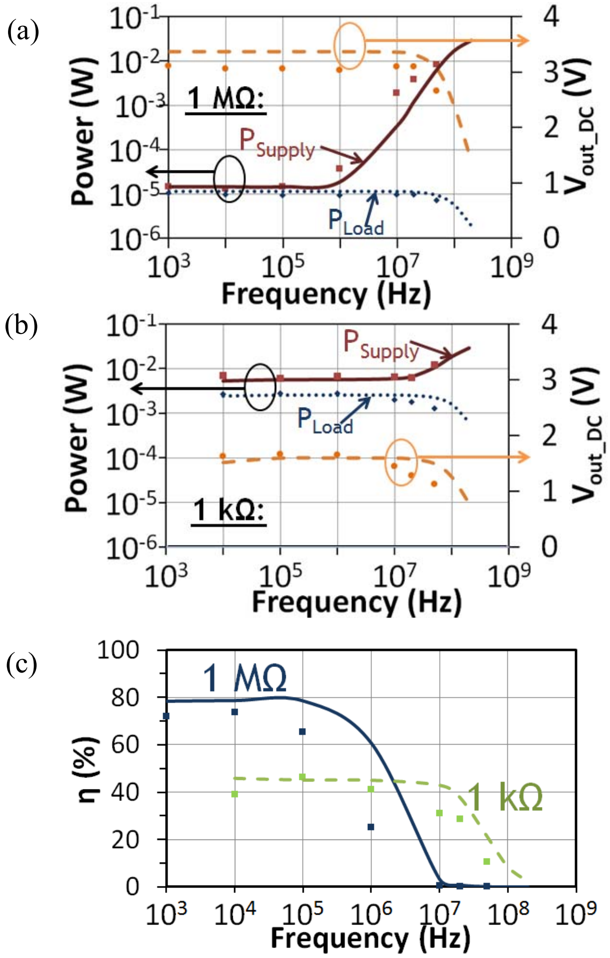

Fig. 5. Measuring the power conversion efficiency of a half-wave rectifier. Points are experimental data and curves are SPICE simulations. (a) P_{Load}, P_{Supply} and V_{out_DC} as a function of input source (V_{in}) frequency, with a 4 V amplitude, using a 100 nF and 1MΩ, and (b) 100 nF and 1kΩ parallel load. (c) Power conversion efficiency as function of frequency for these loads.

P_{Supply} is now constant up to 10 MHz before increasing. Thus, the efficiency [Fig. 5(c)] remains above 30% until 10 MHz, before dropping rapidly at higher frequencies. The higher corner frequency of the 1 kΩ load is not due to reduced power dissipated in the series resistor R_S from current through C_J. Rather, it is the result of the higher DC power delivered to the load, making the AC power lost in R_S a reduced factor up to higher frequencies. The power efficiency is lower at low frequencies (45% with 1 kΩ load vs. 80% with 1 MΩ load) due to a larger DC diode drop across the rectifier (lower V_{out_DC}). However, due to the higher corner frequency of P_{supply}, the efficiency remains approximately constant to 10 MHz instead of 100 kHz for the 1 MΩ load.

IV. CONCLUSION

We have demonstrated a hybrid a-Si / nc-Si diode with a high current density. This hybrid structure enables devices with a small diode series resistance (R_S) and small capacitance (C_J), which allows us to carry out AC-to-DC rectification at frequencies greater than 100 MHz, and have a power conversion efficiency $>30\%$ up to 10 MHz. The hybrid Schottky diode is well-suited for developing large-area systems, due to its low processing temperature and the possibility of integration with a-Si TFTs. We have employed it in a sensing sheet for structural health monitoring [3].

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