Measurement of Photo Capacitance in Amorphous Silicon Photodiodes

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Abstract. This paper discusses the photodiode capacitance dependence on imposed light and applied voltage using different devices. The first device is a double amorphous silicon pin-pin photodiode; the second one a crystalline pin diode and the last one a single pin amorphous silicon diode. Double amorphous silicon diodes can be used as (de)multiplexer devices for optical communications. For short range applications, using plastic optical fibres, the WDM (wavelength-division multiplexing) technique can be used in the visible light range to encode multiple signals. Experimental results consist on measurements of the photodiode capacitance under different conditions of imposed light and applied voltage. The relation between the capacitive effects of the double diode and the quality of the semiconductor internal junction will be analysed. The dynamics of charge accumulations will be measured when the photodiode is illuminated by a pulsed monochromatic light.

Keywords: capacitanc**e,** photodiode, amorphous silicon.

1 Introduction

1.1 Research Question and Motivation

The research question that supports the study presented in this paper is: "Is it possible to control the photo capacitance of the double pin-pin photodiode?"

The methodology used to give answer to this research question consists on the comparison of a double pin-pin photodiode based on a-Si:H/a-SiC:H with an amorphous silicon pin device and a crystalline pin diode through the measurement of capacitance-voltage and photocurrent-voltage characteristics. We are interested in the influence of the material and device structure on the photodiode capacitance in order to improve the performance of these devices for WDM applications in the visible range.

1.2 State of the Art and Related Literature. Methodological Approach

In a crystalline silicon pn junction there are two types of capacitances, related to the charge stored in the depletion layer (junction capacitance) and to the diffusion of carriers along the junction (diffusion capacitance) [1].

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When we consider the pn junction under reverse bias conditions, there is an increase in the width and charge of the depletion layer; as the voltage across the device changes, the charge stored in the depletion layer changes as a result. We can observe a correspondence between a capacitor and the depletion layer of a pn junction; the charge stored on either side of the layer is a non linear function of the applied reverse voltage. Under a small-signal approximation the depletion capacitance, or junction capacitance, is the gradient of this curve, at the bias point. On the other hand, we can consider the depletion layer as a parallel-plate capacitor and obtain the expression for its capacitance, using the traditional procedure. When the pn junction is under forward-bias conditions, the depletion layer narrows and the depletion barrier voltage reduces; the diffusion current increases until equilibrium is achieved. In the steady state, a certain amount of excess minority carriers charge is stored in each of the bulk pn regions. If the terminal voltage changes, this charge will have to adjust, before a new steady state is achieved. This charge storage occurrence introduces another capacitive effect, which is directly proportional to the diode current: we are referring the diffusion capacitance.

Nowadays, hydrogenated amorphous silicon and hydrogenated amorphous silicon carbide have found a large application in electronic devices. In this type of pn junctions, we must have special attention to the midgap density of states and junction properties, to obtain the correct expression of the capacity. The pin configuration is frequently used in photo devices; the i-layer may be alloyed with carbon to optimize the band gap for a given application. May be the simplest and most widely applied techniques to characterize mid gap states (i.e. deep levels) in semiconductors are admittance measurements. The imaginary part of the admittance, i.e. the capacitance, is directly related to the charge trapped in or released from mid gap states, as a consequence of time-varying excitation. State occupancy is manipulated by varying the band bending associated with a Schottky barrier or pn junction. The spectral and energetic distribution of states within the space-charge region is probed by varying the frequency, temperature and bias voltage, as seen in [2].

A possible application of these type of photodiodes is in short range optical communications using the multilayered a-SiC:H heterostructure as a wavelength division demultiplexing device [3]. Nowadays optical communications demand the transmission of a huge amount of information. To increase the transmission capacity and to allow bidirectional communication over one strand fibre, wavelength division multiplexing (WDM) is used. This technique consists on combining multiple wavelength optical signals on a single optical fibre. To perform such task the WDM system uses a multiplexer at the transmitter to mix the signals and a demultiplexer at the receiver to split them apart [4, 5]. The pin-pin diode used in this analysis was designed to work as an optical filter, with selective wavelength sensitivity. Both pin structures of this device were optimized for selective collection of photo generated carriers. Band gap engineering was considered to adjust the photo generation and recombination rates of the intrinsic region of each diode, taking into account wavelength absorption and carrier collection in the visible range.

Photo capacitive effects influence the device frequency response under transient conditions. As a WDM device is intended to be used to increase the bandwidth of the optical communication system the transmission rate must be kept as high as possible. Capacitive effects result in signal degradation and induce errors at the reception end [2], which is an important limitative aspect for the device performance. In order to minimize this effect it is important to understand the mechanisms responsible for the device photo capacitance.

Capacitance values are evaluated considering the impedance of the device in study.

2 Contribution to Internet of Things

The Internet of Things is a "vision" that is being created these days. It concerns the idea of expanding communication among things. This will bring the ability of objects performance to change due to what they contact through the internet. In the particular case of optical communications in the visible range, recent research and new sensor devices, for instance WDM (wavelength-division multiplexing), will contribute to innovation and new resources and capabilities. And that will contribute to the future development of the Internet of Things.

3 Research Contribution and Innovation

Measurements of capacitance were made with different photodiodes, under different illumination conditions and changing the applied voltage. Three different devices were used in these experiments: a commercial crystalline silicon pin photodiode (Vishay Semiconductors BVP10), an amorphous silicon pin photodiode and a pin-pin structure based on amorphous silicon and amorphous silicon carbide. The a-Si:H devices were produced by PECVD (Plasma Enhanced Chemical Vapour Deposition) The pin-pin device structure consists of a p-i'(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure with low conductivity doped layers. Our goal was to point out the different behaviours of the devices and to relate these differences to the structure composition and to the material used. The light incident onto the diodes was obtained by a white lamp and a colour filter covering the light source. The measurements were performed using a pulsed monochromatic light with a frequency ranging from 10 Hz up to 1 kHz. From the WDM application point of view, these frequencies are indeed very low. We have chosen this measurement condition for permitting a clear analysis about the influence of the materials and interfaces properties on the device capacitance.

4 Discussion of Results and Critical View

In Fig. 1 it is reported the CV measurement of an a-Si:H pin photodiode, under dark conditions and using illumination with different wavelengths (red: 626 nm, green: 510 nm, and blue: 430 nm). The device is biased in the range -1V up to +1V.

Results show that in dark the capacitance does not change with the applied voltage, either under reverse and forward bias. Under illumination, a different behaviour is observed, as the capacitance changes with the voltage and in the analysed bias range it takes higher values. The highest capacitances are observed under red illumination; the medium capacitance values are observed under green light; and at last the smallest ones under blue light.

Under reverse bias (-1V) the capacitance under blue and green light match the dark capacitance, while the capacitance under red illumination is slightly higher. However, as the voltage increases the capacitance under illumination increases at different rates.

This is in agreement with the classical theory of the junction capacitance.

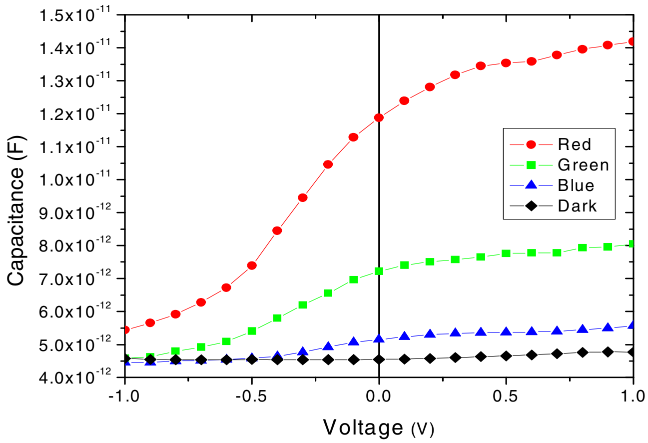

Fig. 1. Capacitance-voltage characteristics of an a-Si:H photodiode, under dark condition and under illumination with different wavelengths (red, green, and blue)

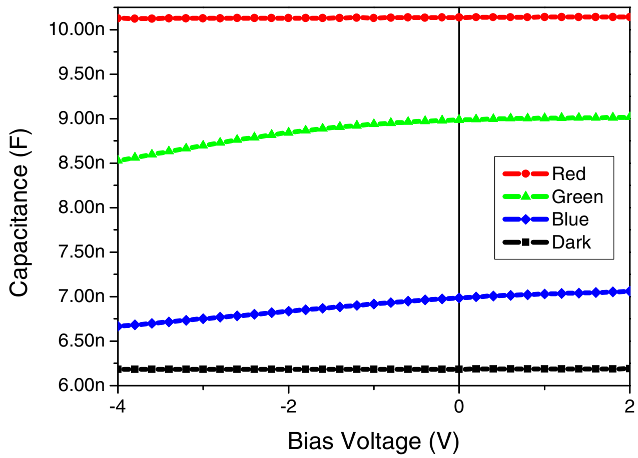

Fig. 2. Capacitance-voltage characteristics of a pin-pin photodiode, under dark condition and under illumination with different wavelengths (red, green, and blue)

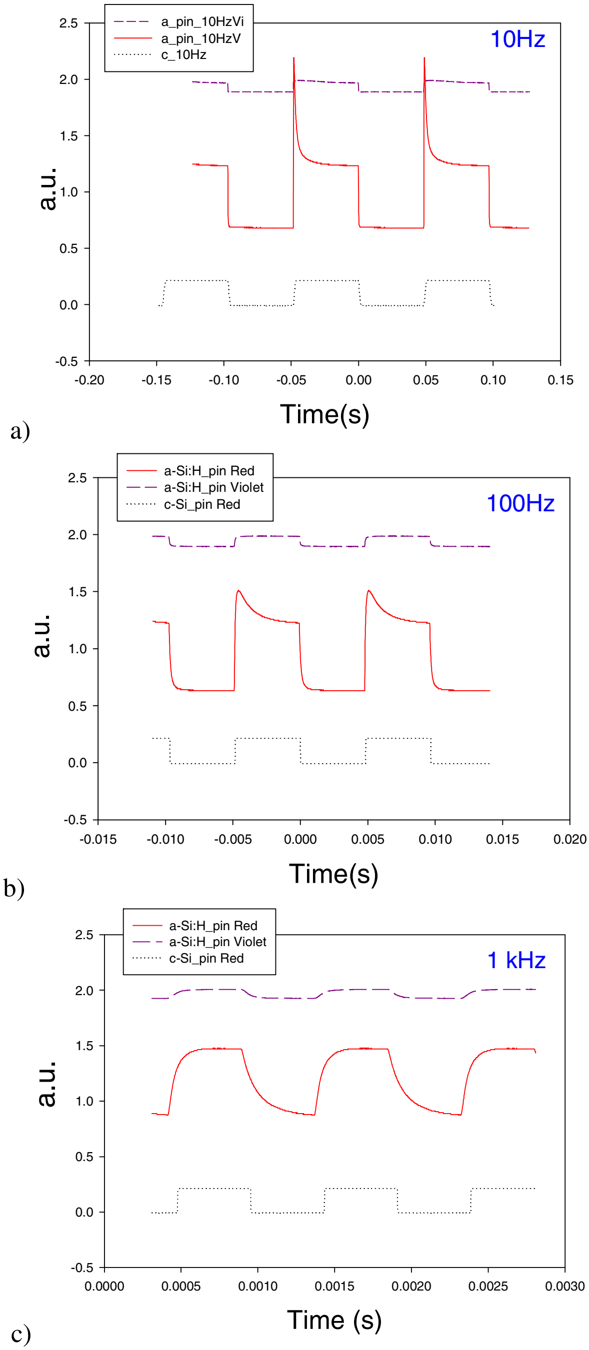

Fig. 3. Comparison of the transient response of the c-Si diode under a pulsed red light and the a-SI:H pin diode under red and blue pulsed light: a) 10 Hz, b) 100Hz and c) 1 kHz

In Fig. 2 we can see the CV measurement referred to a pin-pin photodiode. The value of the light induced capacitance depends slightly on the applied bias, on the light intensity. And it varies with light wavelength greatly; the red colour corresponds to the higher values of capacitance. Comparing the pin diode with the pin-pin device we can see that both capacitances vary with applied bias and with light wavelength, being the capacitance in the pin-pin structure much higher than the pin one.

Considering imposed red light, the pin diode has a major increase in the value of capacitance, as the value of bias voltage gets higher; in the case of the pin-pin diode, the capacitance value is very high, but remains constant, regardless the bias voltage value. In the case of green and blue light, the capacitance changes are very similar.

In Fig. 3 it is reported the comparison of the transient response of the crystalline silicon diode (c-Si diode) under a pulsed red light, used as reference term, and the hydrogenated amorphous silicon diode (a-Si:H pin diode) under red and blue pulsed light, with different frequencies: 10 Hz, 100Hz and 1 kHz, namely a), b) and c).

In Fig. 3 - a), b) and c), the inferior trace of each plot shows the behaviour of the crystalline diode, under red pulsed light. We can see a similar pulsed photocurrent as a function of time, as the diode response. In the classical theory, capacitive effects of the device were not expected.

In Fig. 3 – a), b) and c), the central image in each one show the response of an amorphous pin diode under red pulsed light. A transient photocurrent, as a function of the time, is the response of this experiment. A peak value of current can be recognized; for small values of frequency, 100 Hz and specially 10 Hz, the amorphous photodiode photo current has a peak of intensity, in the beginning of each time period. It repeats the behaviour of a RC circuit in transient regime.

Using a different colour of pulsed light (violet), as we can see in the superior images of each figure 3 –a), b) and c), the amorphous silicon diode response is similar to the applied pulsed light.

In Fig. 3 – c) the frequency used is 1 kHz. The crystalline diode keeps its response stable and the amorphous photodiodes have different responses, similar to the previous plots, but on a smaller scale.

In Fig. 4 we present the time response of a double amorphous silicon device, a pin-pin diode, for different wavelengths of pulsed light. The red, green and blue imposed lights are transformed in transient photocurrents, with a maximum and a minimum values, during a time period, whose rising and decaying times are a little different. The peak values are obtained under the red colour, and the smaller ones under the blue colour, recalling the behaviour of a RC circuit in transient regime.

The charging and discharging times to and from the offset photocurrent value are different. This may lead to conclude that the two processes are made on different paths with different resistance or/and capacitance characteristics.

Observed values for the capacitance of the pin-pin are higher than for the pin device, which may be related to the presence of two double pin structures stacked

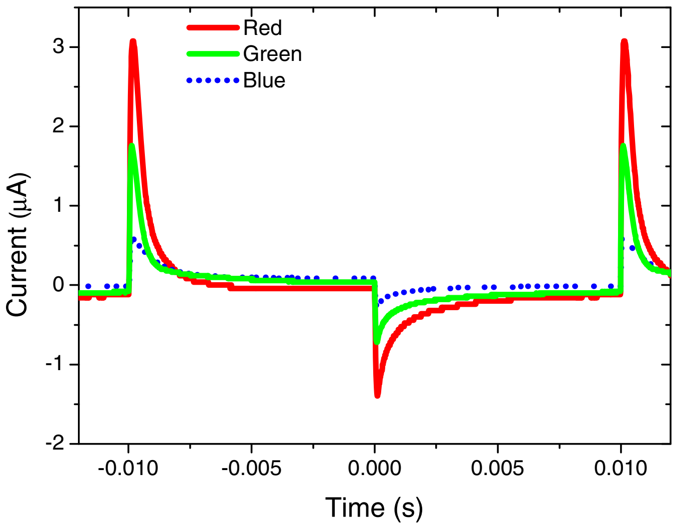

Fig. 4. Time response in a pin-pin diode, showing the photo current for different wavelengths (red, green and blue colours)

together. From this configuration results an additional internal pn junction causing a separation of the trapped charge within the two active layers of the device. Also a higher series resistance is expected in the double diode configuration.

5 Conclusions and Further Work

Diode photo capacitance varies with different parameters. Considering the crystalline diode, the photocurrent follows the imposed pulsed light showing no capacitive effect; it is independent of its frequency and colour.

In the case of an amorphous pin diode the photocurrent presents a transient behaviour that is consistent with charge and discharge of a capacitive circuit. Its highest value is present when the frequency value is low, and when the pulsed light is red.

Considering the double pin-pin diode, the time response has two peaks in a time period, one positive and the other, smaller, negative. They expose the capacitive effects in this device; capacitance values also depend on light wavelength, the highest values for the red colour. These results permitted to relate the photodiode behaviour with the device characteristics of capacitance and resistance.

In future work it will be useful to make measurements of different devices with varying thickness of the absorbing layers. Also the influence of the defect densities in the intrinsic layer should be studied. These results should be confirmed by electronic simulation based on an equivalent model of the device that is being tested. And the study will be extended to higher values of frequency, up to 1 GHz.

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