Operation of Fast Recovery Diode at Low Temperature

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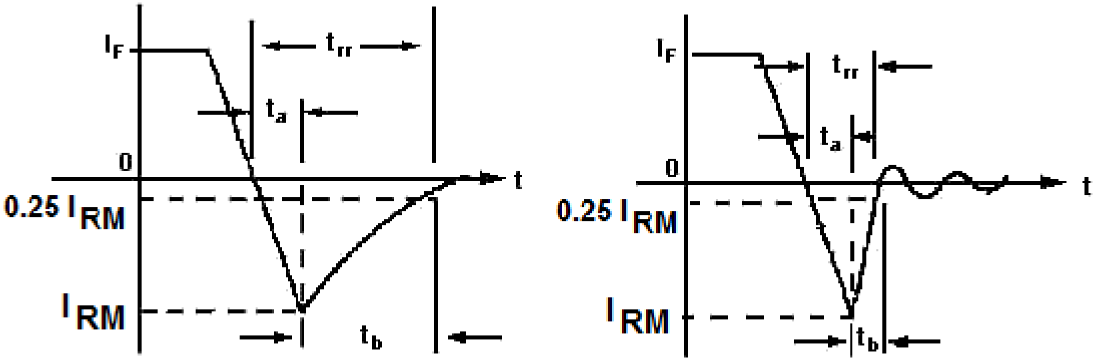
Abstract:

The present work was mainly concerned with improving the reverse recovery times of fast recovery diode applying low temperature during the diode operation. In this concern, the static characteristics of the device have firstly been studied at room temperature to get basic device performance, including DC characteristics (current-voltage characteristics, I-V) and AC characteristics (capacitance-frequency characteristics C-f) of fast recovery diode type FR101, as an example under ascending levels of temperature ranging from 298 k down to 100 k at frequency level of 1MHz. Meanwhile, the diode threshold voltage, junction capacitance, and the reverse recovery parameters including: the reverse recovery times, reverse recovery charge, reverse recovery current are all studied as a function of low temperature. From the results, it was observed that the reverse recovery parameters of fast recovery diode are direct degraded functions of low temperature. Also, the study showed that the reverse recovery phenomenon was observed to be soft at room temperature and changed to abrupt below 273 k.

Introduction

In the forward-biased junction diodes, the electrical current consists of majority and minority carriers. A small current will continue to conduct for a small amount of time after the forward current (I_F) of a forward conducting diode has been reduced to zero, due to minority carriers stored in the PN junction and bulk semiconductor material,. These minority carriers require some finite time (reverse recovery time, t_{rr}) to recombine with opposite charges to be neutralized **[1-4]**. There are two reverse recovery characteristics for the diode, namely, soft recovery and abrupt recovery (Fig. 1).



(a) (b)

Fig. 1. Reverse recovery characteristics of diodes: (a) soft recovery and (b) abrupt recovery.

The abrupt reverse recovery occurs when the Softness Factor (SF) is ≤ 1, and it is responsible for producing extremely reverse current rating (di/dt), which produces large spike voltages (V_{spike}) across any stray inductances that are in series with the diode. So, a snubber circuit is required **[5-7]**. Whereas, when SF is > 1 a soft recovery occurs. As shown in Fig. 1, the maximum reverse recovery current (I_{RM}) could be calculated by applying Eq. (2.1). Where,

$$I_{RM} = t_a \frac{di}{dt} \quad \textbf{(1)}$$

Where:

t_a: Time due to charge stored in the junction (time between zero crossing and I_{RM}).

The reverse recovery time (measured from the initial zero crossing from forward conduction to reverse blocking condition of the diode current to 25 % of I_{RM}) could be calculated by applying Eq. (2)

$$\mathbf{t_{rr} = t_a + t_b} \quad \textbf{(2)}$$

Where:

t_b: Time due to charge stored in bulk material (time between I_{RM} and 25% of its value).

The magnitude of t_{rr} depends on:

1. Junction temperature,
2. I_F and
3. Rate of change of forward current (dI_f / dt).

The softness factor could be calculated applying Eq. (3).

$$SF = \frac{t_b}{t_a} \quad \textbf{(3)}$$

Due to changeover from forward conduction to reverse blocking condition, a reverse recovery charge (Q_{RR}) which is the amount of charge carriers that flow across the diode in the reverse direction is produced. Here, its value is determined from the area enclosed by the path of the reverse recovery current, that is:

$$Q_{RR} = \frac{1}{2} I_{RM} t_a + \frac{1}{2} I_{RM} t_b = \frac{1}{2} I_{RM} t_{rr} \quad \textbf{(4)}$$

$$I_{RM} = \frac{2 Q_{RR}}{t_{rr}} \quad \textbf{(5)}$$

From Eq's. (1) and (5), one gets;

$$I_{RM} = \frac{2Q_{RR}}{t_{rr}} = t_a \frac{di}{dt} \quad \textbf{(6)}$$

If t_b is negligible in comparison to t_a, then:

$$t_{rr} = t_a \quad \textbf{(7)}$$

Hence, Eq. (7) becomes;

$$t_{rr} = \sqrt{\frac{2Q_{RR}}{di/dt}} \quad \textbf{(8)}$$

and,

$$I_{RM} = \frac{2Q_{RR}}{t_{rr}} = \sqrt{2Q_{RR}\frac{di}{dt}} \quad \textbf{(9)}$$

The charge storage problem of a PN junction could be eliminated in Schottky diodes **[6, 8-10]**. Where, such devices are constructed from depositing a metal layer on a thin epitaxial layer of N-type silicon semi-conductor, producing a potential barrier with an ohmic contact or non-rectifying connection between a metal and semiconductor. The ohmic contact of Schottky diode depends only on; the majority carrier and as a result there are no excess minority carriers to recombine. It is to be noticed that, Schottky diodes have some drawbacks such as:

i) Limited high-temperature operation
ii) High leakage current (Is) values.
iii) The break down voltage (V_{BR}) of the silicon Schottky diode cannot be reliably made larger than 200 Volts.

The fast recovery diodes cover voltage ratings from 50 V up - to 3.0 kV and current ratings from less than 1.0 A to hundreds of amperes **[11]**. So, they are necessary for modern power electronic systems **[12]**. They have a low t_{rr} value, normally less than 5.0 μs, and stop conducting quickly when a reverse charge is imposed across their junction. In practice, they are mainly used in DC-DC converters and DC-AC inverter circuits, where they

The present paper aims improve the reverse recovery characteristics of fast recovery diode applying low temperature.

There are different studies have come up for studying and improving the characteristics of reverse recovery diodes and some of them are introduced in the following part as examples. In 2007, F. Cappelluti, et al. presented a study that introduced the application of physics-based mixed-mode simulations to the analysis and optimization of the reverse recovery for Si-based fast recovery diodes using Platinum lifetime killing. The trap model parameters are extracted from Deep Level Transient Spectroscopy characterization. An improved design, using emitter control efficiency and merged PiN–Schottky structures was analyzed. The results were compared with the simulated ones **[13]**. During the year 2012, Chengjie Wang, Li Yin, and Chuanmin Wang introduced a paper that presents a physics- based model for highly-voltage fast recovery diodes. During the study, a good trade-off between reverse recovery time and the forward voltage drop was observed through a combination of life time control and emitter efficiency reduction techniques. The results showed that decreasing the excess carriers stored in the drift region led to softer characteristics. The experimental results showed good agreement with the model **[14]**.

During the work, the effect of the low temperature on the reverse recovery characteristics of fast recovery diode is investigated. So, some of electrical parameters affecting the reverse recovery characteristics are firstly investigated under the effect of low temperature. In this concern, the junction capacitance and the threshold voltage of the diode are studied as a function of temperature levels ranging from 298 k to 100 k. After that, the reverse recovery characteristics are studied as well as the recovery times, softness factor (SF), reverse recovery current (I_{RM}), and reverse recovery charge (Q_{rr}) are all calculated/measured at operating frequency of 1 MHz.

2.0 Experimental Details

The aim of this paper is to study and present the effect of the low temperature on the reverse recovery characteristics of fast recovery diode. So, some of electrical parameters affecting the reverse recovery characteristics are firstly investigated under the effect of low temperature. The experimental procedures are carried out as the following:

- The static characteristics of the device have firstly been studied at room temperature to get basic device performance, including DC characteristics (current-voltage characteristics, I-V) using a 370A programmable curve tracer and AC characteristics (capacitance-frequency characteristics C-f) using programmable Fluke RCL bridge.

- The diode is exposed to different temperature levels ranging from (100 k up to 298 k) using the cooling system illustrated in Fig. (2) and its temperature is measured using digital thermometer type BK Precision 710 when the diode is put in the glass container surrounded by liquid Nitrogen. During the measurements, A K-type thermocouple is used as a temperature sensor with an accuracy of ±0.2% rdg+2℉ (±0.2% rdg+1℃).

- The junction capacitance and the I-V characteristics of the diode, as well the threshold voltage are studied as a function of temperature levels ranging from (298 k to 100 k).

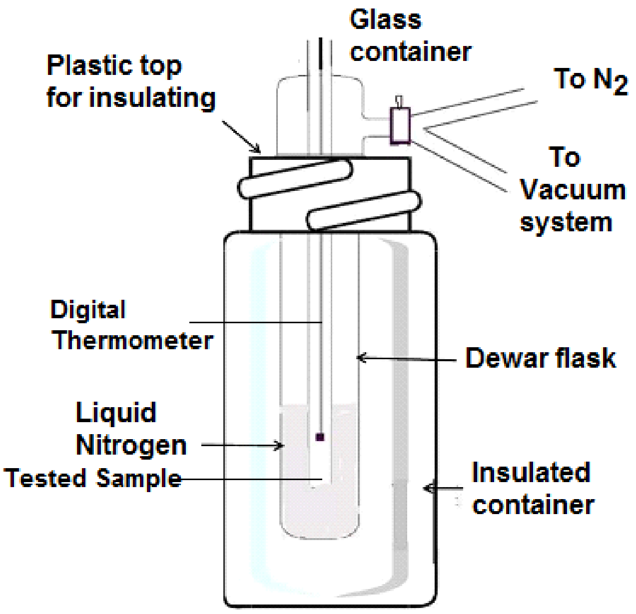


Fig.2. Designed cooling system for controlling the low temperature levels of the samples.

In order to study the reverse recovery characteristics of the proposed diodes, a square wave pulse was applied to the diode (when exposed to the investigated temperature range) with voltage amplitude of 3.0 Volts and f_s of 1 MHz. The output voltage across R_L value of 100 Ω and I_o passing through it were measured, where;

$$I_o = \frac{V_o}{R_L} \quad \textbf{(10)}$$

In addition, the following parameters; t_a, t_b, t_{rr}, I_{RM}, Q_{rr} and SF are calculated. The test circuit for reverse recovery characteristics **[15]** is shown in Fig. (3).

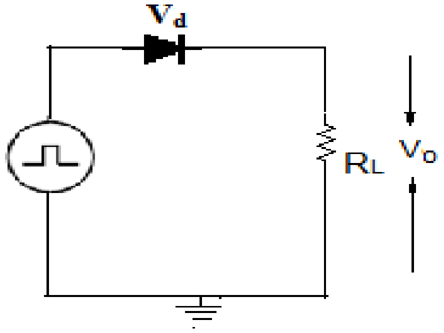


Fig. 3. Circuit for reverse recovery characteristics of power diodes

The reverse recovery characteristics are studied, as well the recovery times, SF, I_{RM}, and Q_{rr} are all calculated/measured at operating frequency of 1 MHz under the temperature levels from (100 k up-to298 k).

3.0 Results and Discussions

The effect of low temperature is noted on the (I-V) characteristic curve of the tested diode (Fig.4a). V_{Th} and as a function of temperature are derived from this as shown in Fig. 4b. From which, it is clearly indicated that V_{Th} is linearly increased with temperature decrease by the ratio of 34.93 % of the initial value.

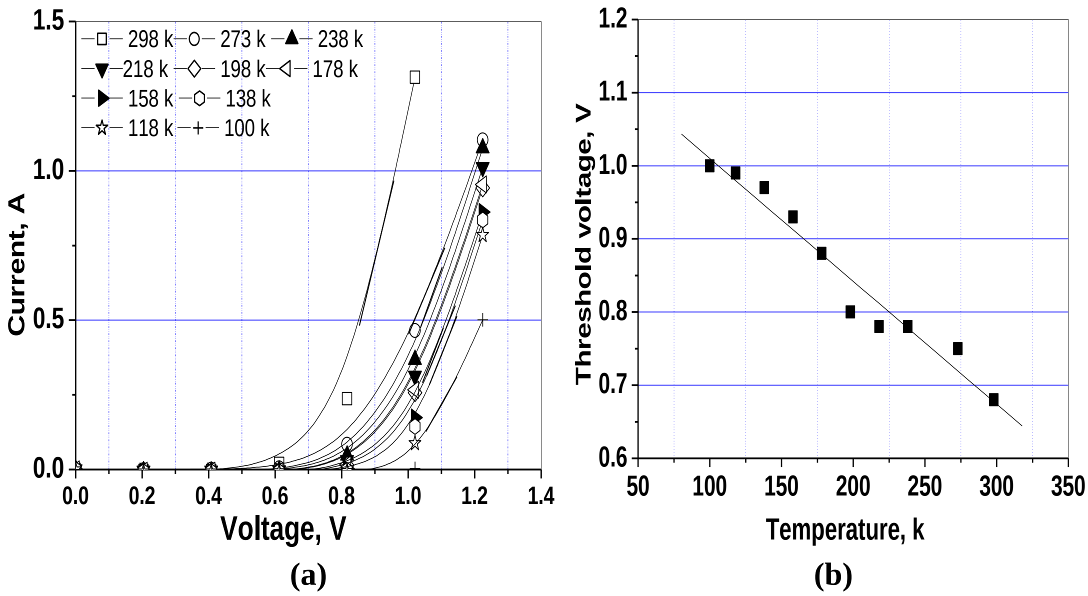


Fig. 4. Impact of temperature on; (a) I-V curve and (b) threshold voltage of fast recovery diode

Fig.5 shows (C-f) characteristics of the diode (the dependence of diode junction on frequency) at different temperature levels ranging from 298 k down-to 100 k, studied at blocking voltage of 10 V. This demonstrates that for the different temperature levels the diode junction capacitance is observed to be decreased by decreasing the frequency up to 2 kHz, after which its value remained nearly constant.

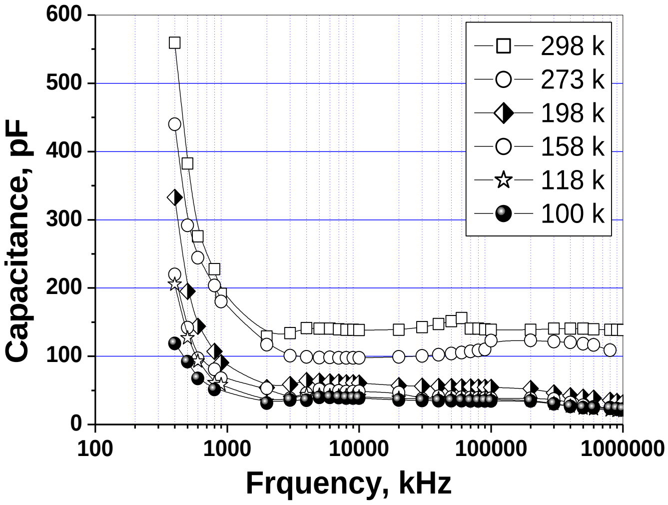


Fig. 5. Effect of frequency on junction capacitance of the investigated diode, plotted for different temperature levels

Concerning, the dependence of diode junction capacitance on temperature (Fig.6). It is to be observed that, its value is decreasing function with temperature decrease till the value of 158 k, after that its value is observed to be saturated at 21.06 pF. Whereas, the initial value is measured to be 139.7 pF.

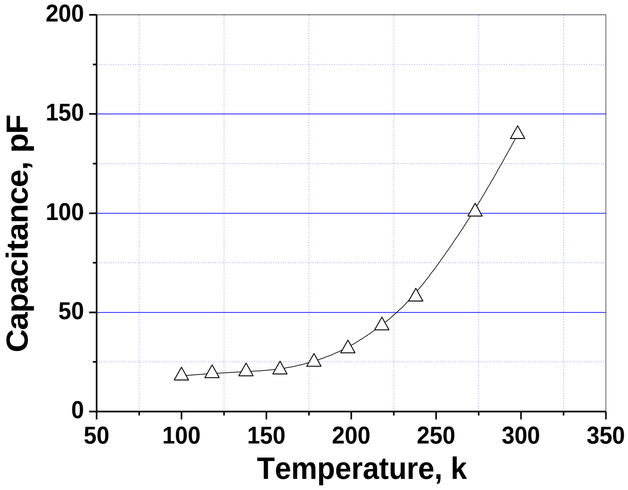


Fig.6. Effect of temperature on junction capacitance of the investigated diode, plotted at 1MHz.

Considering the dependence of the reverse recovery characteristics on temperature (Fig. 7). It is clearly observed that the cooling process of the investigated diode converts the reverse recovery phenomenon to abrupt phenomenon, where a parasitic ringing is observed at 100 k.

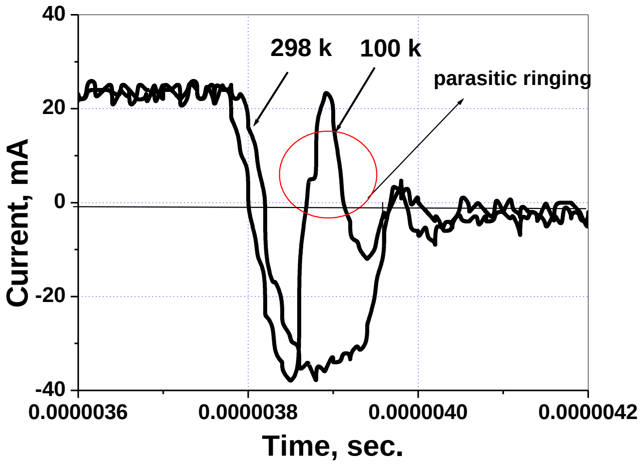
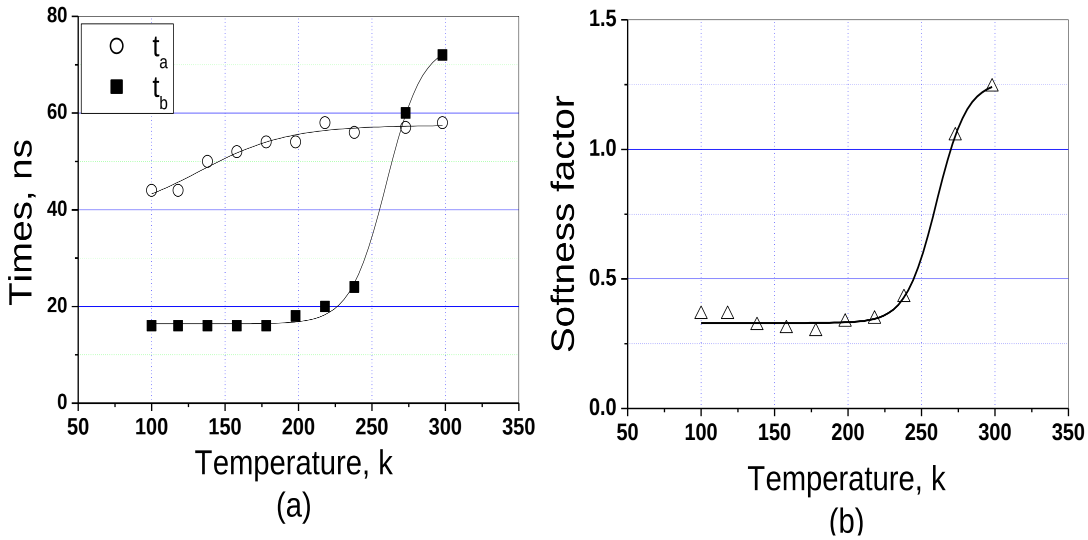


Fig. 7. The reverse recovery phenomenon of the investigated fast recovery diode, plotted at 100 k and 298 k.

Moreover, Fig. 8a shows the reverse recovery times (t_a and t_b) of the selected fast recovery diode and it is seen that at room temperature (298 k), t_b is higher that t_a, which means the reverse recovery phenomenon is soft **[6]**. It was noted that the calculated softness factor is higher than 1 (1.24) shown in Fig. 8b while, on exposing the sample to low temperature, the time decreased and t_b became lower than t_a and started from a temperature lower than 273 k. The observed results mean that the recovery phenomenon is abrupt at low temperature, where SF was shown to be lower than 1 (0.42). The mean reason for decreasing the recovery times is attributed to the decrease in the junction capacitance **[6]** as shown in Fig. 6, as well as the decrease in the minority carriers expressed by the decrease in the reverse recovery current **[6]** as shown in Fig.(8c).Where, it is to be noticed that I_{RM} is decreased from 37.2 mA at 298 k down to 36.4 mA at 178 k. Meanwhile, Q_{RR} values are decreased from 2.44 nC, measured at 298 k and decreased to 2.25 nC at 118 k.



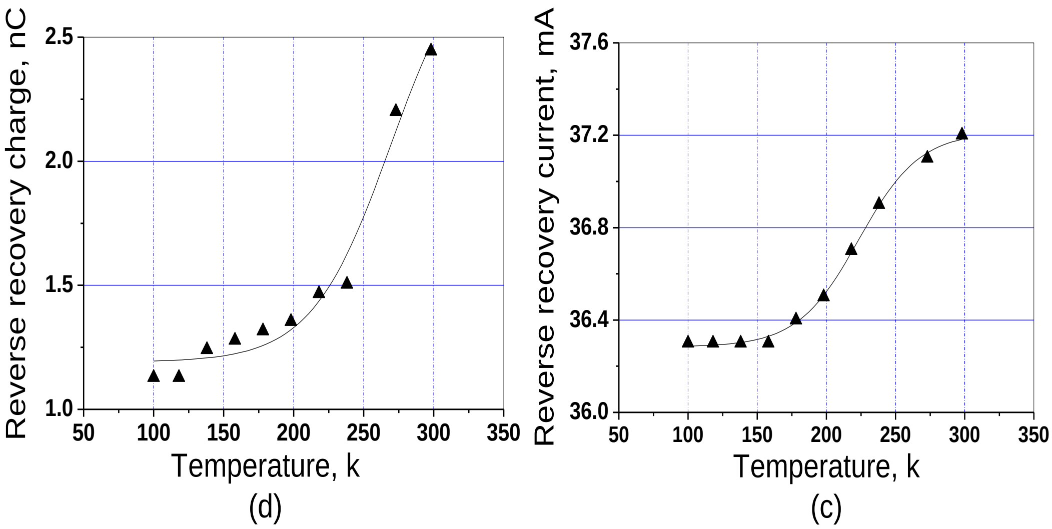


Fig. 8. Effect of low temperature on (a) reverse recovery times, (b) softness factor, (c) reverse recovery current, and (d) reverse recovery charge of fast recovery diode, plotted at 1MHz.

Conclusion

In the present paper, the effect of the low temperature on the reverse recovery characteristics of fast recovery diode is investigated. During the work, the static characteristics of the device have firstly been studied at room temperature to get basic device performance, including DC characteristics (current-voltage characteristics, I-V) and AC characteristics (capacitance-frequency characteristics C-f).

- The diode is exposed to different temperature levels ranging from (100 k up to 298 k)
- The junction capacitance and the I-V characteristics of the diode, as well the threshold voltage are studied as a function of temperature.
- The reverse recovery characteristics are studied, as well the recovery times, SF, I_{RM}, and Q_{rr} are all calculated / measured at operating frequency of 1 MHz under the same temperature levels.

From the results, it is observed that the reverse recovery parameters of fast recovery diode are direct degraded functions of low temperature. Also, the study showed that the reverse recovery phenomenon was observed to be soft at room temperature and changed to abrupt below 273 k.

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