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Voltage oscillations during surge pulses induced by self-extinguishing non-destructive second breakdown in pn-junction diodes

Steffen Holland*, Rolf Brenner

Nexperia Germany GmbH, Stresemannallee 101, 22529 Hamburg, Germany

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ABSTRACT

PN-junction diodes with different breakdown voltages have been subjected to surge pulses per the standard IEC 61000-4-5 and their transient behaviour has been studied. For medium breakdown voltages (20–40 V) at high surge currents large transient oscillations in the voltage drop across the diodes are observed. After such an event, the devices are still operational. 3D electro-thermal TCAD simulations have been done to understand the phenomenon. A comparison between measurement and simulation reveals that the periodic voltage drop is caused by non-destructive second breakdown.

1. Introduction

When semiconductor devices are subjected to events which cause electrical overcurrent, such as ESD or surge pulses, strong Joule heating raises the temperature inside the device. This self-heating mostly occurs where large electric fields are present such as reverse biased pn-junctions. If the device becomes very hot second breakdown occurs eventually: the current constricts, the temperature inside the filament suddenly rises and the melting temperature of the semiconductor material is reached quickly. In measurements, the current constriction is accompanied by a sudden drop of the voltage across the device [1, 2]. It is caused by a self-enhancing effect: the high local current density causes a high temperature and the thermal generation of carriers becomes stronger than the reduced avalanche generation. These excess charges lower the resistance causing even more current to flow through that location leading to a thermal runaway. Typically, the device shows a large leakage current indicating a failure of the device because the pn-junction has been damaged. If and how quickly the device enters second breakdown depends on the power dissipated inside the device and the pulse width which can range from ESD events to DC conditions. Therefore, second breakdown is linked closely to the Safe Operating Area (SOA) of a device which needs to be defined by the device manufacturer so that the device does not fail in the application. The SOA of the devices depend on how they are used in the application. Examples of investigations are found here [3–5].

In this paper, it is shown that second breakdown does need not to be necessarily fatal for the device if subjected to surge pulses. However, when integrated in certain applications, where the device is connected to a power line, it could be destroyed or cause problems for the application. Therefore, using the leakage current after a test as the only failure criterion is not sufficient but the transient voltage needs to be monitored as well. Measurement results are presented and TCAD simulations are used to explain the observed phenomena.

2. Experimental results

The investigated samples are pn-junction diodes. They consist of a highly-doped N-type substrate, a lowly doped epitaxial layer, a deep N diffusion and a shallow P diffusion. In Fig. 1, a cross section of the doping regions is shown. By tuning the doping levels of the deep N and shallow P region, the breakdown voltage can be adjusted to the desired value. The overlap of the P region over the N region into the lowly doped epitaxial layer ensures that avalanche breakdown occurs in the centre of the diode. A UCS-500 M surge generator from EM Test was used to apply surge pulses per IEC 61000-4-5. Fig. 2 shows transient voltage curves for different surge currents applied to a diode with a breakdown voltage of 27 V. The curves have been recorded using the same device and the behaviour can be repeated if a diode from the same series is taken. At low surge currents the transient voltage shows a characteristic hump which is caused by the temperature dependence of the breakdown voltage and mobility as well as the series resistances. At higher surge currents the behaviour of the transient voltage suddenly changes dramatically. After reaching a maximum, the voltage starts to oscillate with a peak-to-peak amplitude of around 30 V. At even higher

* Corresponding author.
E-mail address: steffen.holland@nexperia.com (S. Holland).

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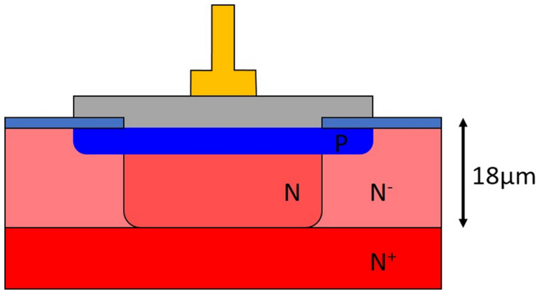

Fig. 1. Schematic cross section of the used pn-junction diodes including a bond wire which connects to the anode. The current flows vertically from top to bottom.

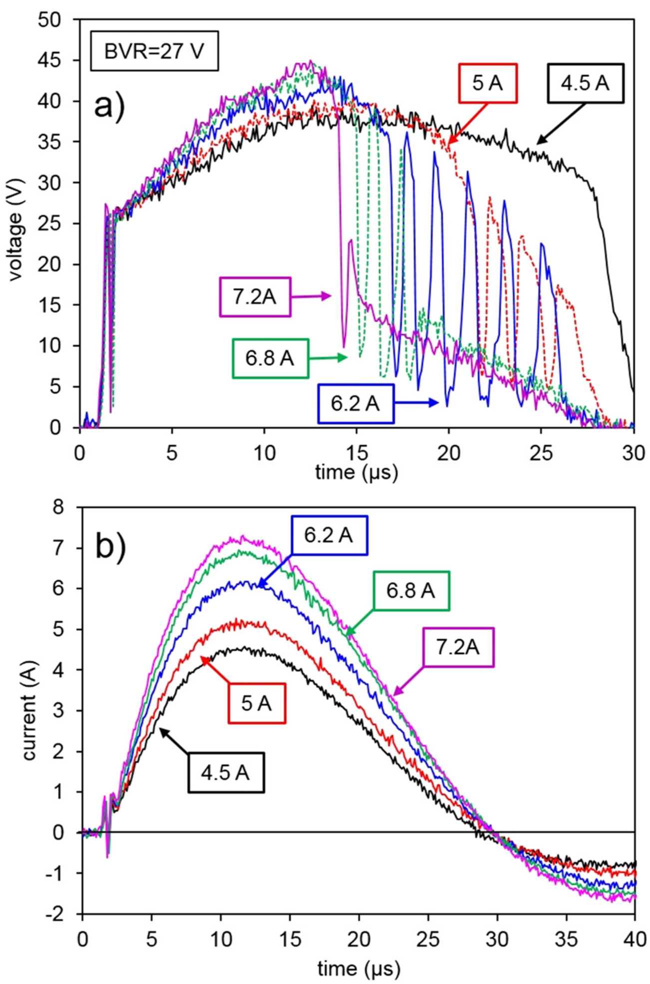

Fig. 2. a) Transient voltages and b) transient current of a diode with 27 V breakdown voltage. With increasing surge current, voltage oscillations suddenly occur. The onset is shifted to lower value of time when the current is increased. At very high currents, the oscillations are suppressed and the voltage stays at a reduced value. The diode is only destroyed at the surge current of 7.2 A. The shape of the transient current is not changed for all measured pulses.

surge currents the voltage does not oscillate any longer but stays at a low value. Similar oscillations have been observed in [6]. The oscillations start earlier when the surge current is increased. For high surge currents the oscillations are suppressed at larger values of time. During measurement an automatic leakage current test at a voltage a few volts below the breakdown voltage has been done. The diodes do not suffer from leakage current and are fully functional after a surge pulse which caused such voltage oscillations. However, it must be noted that the

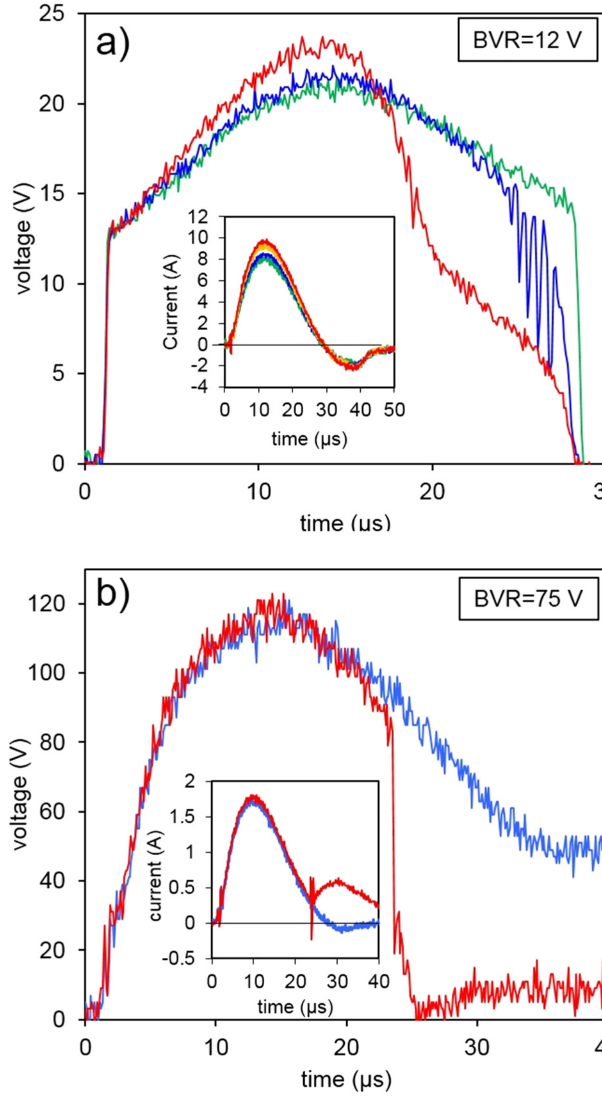

Fig. 3. Transient voltage for devices with a) 12 V, b) 75 V breakdown voltage. The insets show the transient current. The red curve corresponds to a pulse where the device is damaged. The suddenly rising current in b) is caused by the interaction of the DUT and the pulse generator; because of the sudden voltage drop due to second breakdown in the diode, the effective charging voltage and thus the current rises. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

transient voltage drops considerably below the breakdown voltage. At a surge current of 7.2 A the device is eventually destroyed. The behaviour is not limited to this device type but diodes which have breakdown voltages in the range of around 20 to 36 V show the same behaviour. The diode with the next higher breakdown voltage is a 75 V device. This device does not show oscillations as can be seen in Fig. 3b). Due to the lack of devices between breakdown voltages of 36 V and 75 V the boundary where the oscillations do no longer occur cannot be determined more accurately. Fig. 3 shows transient voltages for devices with 12 V and 75 V breakdown voltages for different surge currents. The dimensions are the same as for the 27 V diode. The transient voltage of the 12 V device fails at around 10 A (red curve in Fig. 3a)).

The voltage drop over the diode starts to deviate from the characteristic hump at around 8 A (blue curve). Interestingly, an oscillatory behaviour of the transient voltage starting at around 25 µs can also be observed for this device. However, the amplitude is less pronounced. For the device with 75 V breakdown voltage the current increment, where the device is damaged is very small as can be seen in the inset of