TIME DEPENDENT BEHAVIOUR OF FIELD LIMITING RING PASSIVATION SYSTEMS

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TIME DEPENDENT BEHAVIOUR OF FIELD LIMITING RING PASSIVATION SYSTEMS

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Abstract

Off-state modelling is used extensively within Philips to design field limiting ring passivation systems for switching devices. However, no work has been done to ensure that the quasistatic approach is valid in the transient case. This paper presents the results of fundamental simulations of the pulsed operation of a device with a field limiting ring. These are used to describe the ring's time dependent behaviour in detail and so to identify possible pitfalls in the conventional design approach.

Introduction

Field limiting rings represent a technique widely exploited for the edge passivation of discrete power devices. By reducing the electric field from junction curvature and surface effects, a suitable field limiting ring system can give devices a breakdown voltage approaching that of bulk silicon (see, for example, Kao and Wolley [1]).

Presently field limiting ring passivation schemes are designed within Philips using an off-state device simulator and it is assumed implicitly that a device whose electric field distribution is optimised for off-state operation will also work safely under transient conditions. Since many power devices are used in circuits where they are switched at high frequencies (eg switched mode power supplies), the validity of this assumption is critical to the design methodology. Previously no attempt has been made to verify this.

This paper presents fundamental modelling results from the pulsed operation of a device with a field limiting ring. The results are used to illustrate the mechanism by which the floating ring operates under switching conditions and indications are given as to whether such behaviour could ever become dangerous.

Simulation Results

The simulations were carried out at a fundamental level. In other words, the detailed distributions of potential and mobile charge carriers throughout the device were predicted by performing a consistent solution of Poisson's equation and the time dependent electron and hole continuity equations. The device simulated is a p^+n diode with one p^+ floating ring (see Figure 1) which was subjected to two reverse biassing voltage pulses as shown in Figure 2. Figure 3 depicts the resulting current flow, mainly displacement current, and the variation in the ring voltage (ie the voltage at which the ring floats). To explain the behaviour of the ring in this switching device, it is convenient to divide its operation (and hence Figure 3) into eight regions.

When the first pulse commences (region 1), the depletion region around the main junction begins to expand. The current waveform has the expected shape for a diode subjected to a constant voltage ramp. At $\sim 0.2\mu s$ a hump of current occurs. This coincides with the onset of punchthrough between the main junction and the ring and is caused by the increased capacitance of the system. Displacement current is now supplied by both the main junction and the ring junction. Figure 4(a) clearly displays the electric field pattern at the surface of the device during punchthrough. The plot of hole concentration in Figure 5 shows the expanding depletion region around the ring and the space charge produced by the punchthrough current.

Punchthrough current continues at a high level until the main junction voltage stops falling (at the end of region 2). During this time the voltage difference between the main junction and the ring, that is the punchthrough voltage, gradually increases. This "fan-out" effect is due to the two-dimensional nature of the device.

When the main junction voltage stops falling and remains steady at -200V (region 3), the displacement current quickly diminishes to leave only the leakage current of the reverse biassed diode. The ring voltage suffers a further slow fall due to the decay of displacement current between the ring and the main junction and hence the disappearance of the voltage drop required to support it.

As the main junction voltage rises (region 4), the ring voltage rises with it although at a markedly slower rate. Throughout this phase of operation there is no conductive path between the ring and the main junction as can be seen from the electric field distribution at the surface of the device in Figure 4(b) and the hole concentration in Figure 6. This change in the ring voltage is surprising because the only apparent mechanism by which its stored charge (and hence voltage) could rise is by generation of electron-hole pairs in the depletion region. It can be shown that current from such sources is far too small to explain the observed rate of change of the ring voltage. In fact, the cause of the ring's behaviour is simply the electrostatic coupling of two isolated charged bodies, ie Coulomb interaction. So it is not the internal charge on the ring but the electric fields external to the ring which are causing the ring voltage variation.

A change in the rate of rise of the ring voltage coincides with a second sudden jump in current (at the start of region 5). The cause is the reappearance of punchthrough and so a conductive path between the ring and the main junction once more exists. This is demonstrated by the plot of electric field in Figure 4(c) and the plot of hole concentration in Figure 7. This time holes flow onto the ring, since it is more negative than the main junction, and its depletion region slowly collapses. It is this displacement current that causes the sudden increase in the rate of rise of the ring voltage. The fan-out effect is again noticeable.

When the ring voltage reaches 0V (region 6), punchthrough ceases and the ring is left floating at some voltage below ground. The charge on it can now only decay by leakage current due to generation of carriers. So after $10\mu s$ when the second pulse is applied there is still a voltage remaining on the ring which has the effect of raising the contact voltage required to initiate punchthrough. This is noticeable in the current waveform as a shift in the time at which punchthrough occurs and the current hump appears (see Figure 8). Note that the effect of electrostatic coupling between ring and main junction reappears during region 7.

To summarise, the device's behaviour shows the following features:-

- the displacement current variation with time shows fine structure superposed on the normal waveform for a diode. This is due to the onset of punchthrough to the field limiting ring.
- due to electrostatic coupling effects, a change in the contact voltage causes a change in the ring voltage even when there is no conductive path connecting the two regions.
- at the end of the first pulse the ring is left charged and hence floating at a voltage below ground.
- fan-out is observed, ie the ring voltage does not change at the same rate as the contact voltage.

The first three effects are purely transient phenomena and cannot be modelled quasistatically by off-state simulations.

Experimental Verification

Experimental observations of displacement current show similar features to those seen in the simulations. Figure 9 shows the current waveform for a BU508 bipolar transistor passivated with field limiting rings, which is subjected to repeated voltage pulses where the contact voltage rises at a rate of $10V/\mu s$. This waveform shows both:-

- fine structure in the form of several humps. These features are much smaller than the ones observed in the simulations because of the smaller capacitance of the rings in the experimental case.
- fine structure moving down the waveform as the pulse repetition rate is increased. Again this is because a short time between pulses means that the residual charge left on the rings at the end of one pulse does not decay significantly before the next.

Thus the experimental observations seem consistent with the simulation results.

Discussion of Results

From a device design point of view, the peak electric field within the device is the quantity of importance since this determines whether the device will breakdown. The variation of this with time is shown in Figure 10. Point B on this waveform gives the electric field predicted by off-state simulations. It can be seen that the electric field peaks twice during the first pulse, at A and C, and **not** at B. The difference in electric field between A and B arises from the voltage drop necessary to support the flow of punchthrough current between the main junction and the ring. Thus the size of this difference will depend on the resistance of the punchthrough path (ie the device structure), the voltage ramp rate and the capacitance of the ring system. In the simulations shown here this difference is less than 2% and in most devices will be fairly small.

The peak electric field at C is dictated by the voltage required to punchthrough from the ring to the main junction. In most devices this is very close to the voltage needed for punchthrough from the main junction to the ring. However, point C occurs at the end of region 4 on Figure 3 when electrostatic coupling has already lowered the voltage on the ring and the punchthrough voltage has dropped due to the fan-out effect. So, it would require a device with very asymmetric punchthrough voltages for the field at C ever to exceed that at A.

Conclusions

The results from the fundamental simulations have revealed in detail the mechanism underlying the transient operation of devices with field limiting ring passivation systems. This turned out to be more complicated than initially envisaged. Experimental work has reproduced some of the effects seen in the simulation results and hence supports their validity.

The simulations suggest that the electric fields present under transient operation are very close to those in the steady state except when a significant voltage drop is required to drive punchthrough current between the ring and the main junction. This voltage drop is dependent on the resistance of the punchthrough path, the capacitance of the ring system and the voltage ramp rate.

Our improved understanding of the behaviour of field limiting rings in switching devices has lead to greater confidence in the current quasistatic design methodology as well as indicating its potential limitations.

[1] Y. Kao and E. Wolley, "High Voltage Planar p-n Junctions", Proc. IEEE, 55(8), August 1967.

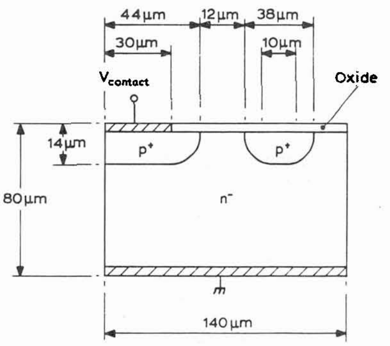

Figure 1. Diode edge passivated with one floating ring.

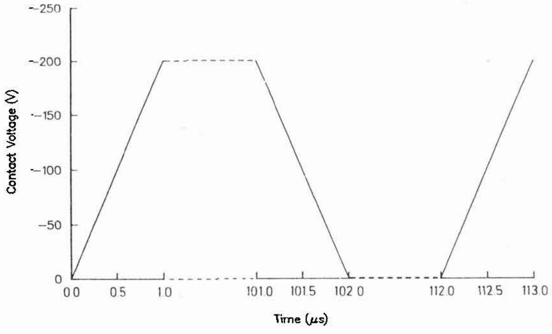

Figure 2. Pulses applied to the main junction contact.

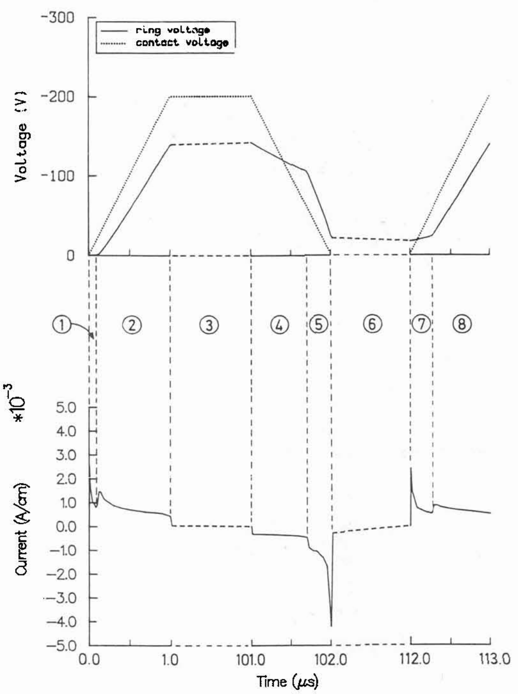

Figure 3. Devices behaviour divided into regions.

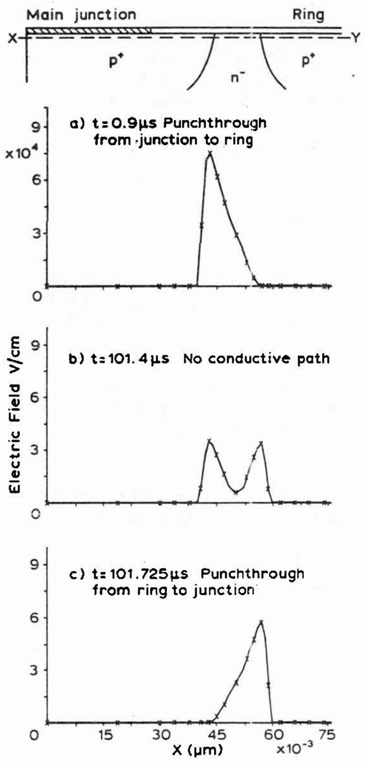

Figure 4. Plots of |E| along the line X-Y.

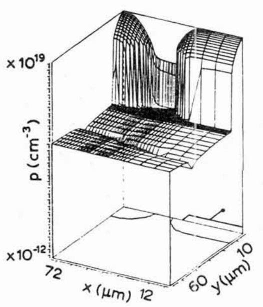

Figure 5. Hole concentration t = 0.7µs

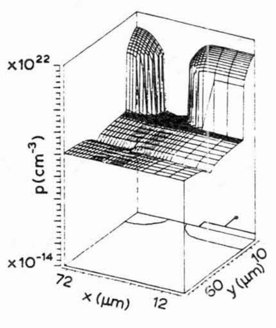

Figure 6. Hole concentration t = 101.4µs

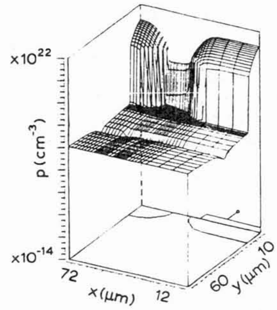

Figure 7. Hole concentration t = 101.725µs

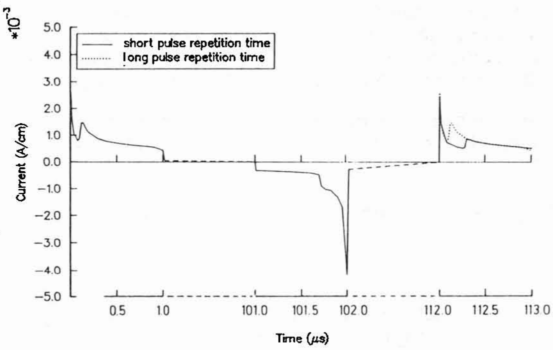

Figure 8. Current v. time.

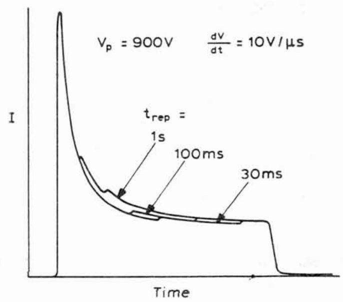

Figure 9. Current-time curves at different repetition times for BU508

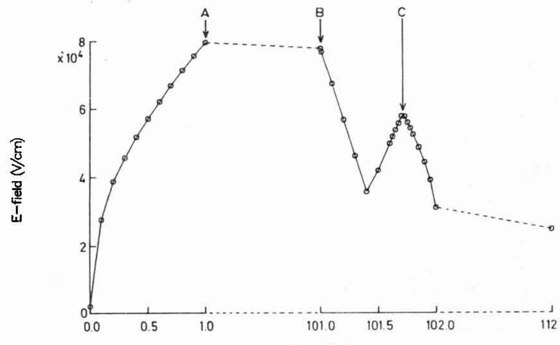

Figure 10. Peak electric field v. time.