Dynamic Behavior of High-Power Diodes Analyzed by EBIC

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A setup is described which allows investigations of electric field distributions in the top layers of a dynamically driven power device by means of time-resolved Electron Beam Induced Currents (EBIC). Functionality of the field termination structures, e.g. guard rings can be visualized under transient bias conditions. Reverse and forward recovery of an 800-V diode was investigated by this technique and the obtained results were compared to EBIC-maps recorded on a statically biased device.

I. INTRODUCTION

Beam-induced current techniques have already been used to observe space charge regions [1, 2] and electric field distributions [3] of high-power devices under static biasing conditions. By time-resolved beam-induced techniques it is possible to determine electric field strengths inside semiconductor devices, as has been demonstrated by simulations and Ion-Beam Induced Charge (IBIC) measurements [4]. The drift velocity of the charge carriers depends on the electric-field strength:

$$v_{drift} = \mu(E) \cdot E \qquad (1)$$

Therefore, the time-dependent parameters, such as the amplitude $I_{\max}$ of the induced current, give information about the electric field distribution inside the device.

As the properties of a high-voltage diode, for example the breakdown voltage, can be very different for static and dynamic conditions, the origins of these differences have to be explored. Therefore, Electron Beam Induced Current (EBIC) investigations under operating conditions are necessary. Thus, the diode must be switched and the EBIC measurements must be performed at different phases during the switching event.

In this paper we show that the temporal evolution of the electric field distribution in the edge region of high-power diodes during switching can be monitored by means of EBIC measurements.

II. MEASUREMENT SETUP

An 800-V diode with a single field ring used as an edge termination was taken as a test structure. During the experiment a focused electron beam is scanned over the surface of the diode. Since the diode surface near the edge termination is protected with a thin passivation layer, 30 keV electrons can penetrate into the semiconductor and generate electron-hole pairs. These charge-carrier pairs are separated by the electric field and generate the EBIC-signal. As already described in [4] this current can be related to the electric field strength at the corresponding place of charge-carrier generation.

Switching of the diode is periodically repeated by a standard electrical circuit, which is usually used for reverse recovery characterization. To obtain time-resolved information of the electric field distribution, the electron beam must be blanked in phase with respect to diode switching. The switching transient has amplitudes of several amperes (as shown in Fig. 3), while the EBIC signals are in the range of micro amperes. Thus, the signal-to-background level is extremely low, as the EBIC-signal can not be separated from the switching transient in time domain. Filtering in the frequency domain is also not possible due to similar spectra of the signals.

The problem is solved using the principle of a Wheatstone bridge. It consists of two parallel-connected branches each containing a diode of the same type and an impedance connected in series with the respective diode (Fig. 1). This Wheatstone bridge is driven by the switching circuit mentioned above. By adjusting the two impedances in the bridge, the difference in the voltage drop across is reduced to a minimum. Since only one of the diodes is exposed to the blanked electron beam, the induced current generates a voltage drop over the corresponding impedance. The voltage difference between the two impedances is fed to an instrumentation amplifier. The output current of the amplifier is detected by a measuring coil for potential free signal processing.

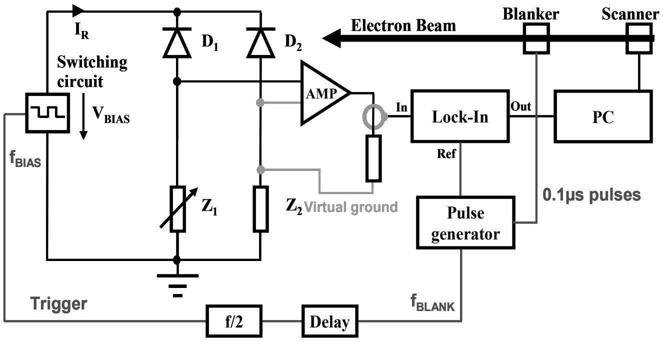

Fig. 1. Measurement setup for EBIC microscopy on dynamically biased High-power Diodes

The decoupled EBIC-signal is then amplified using a lock-in amplifier which has the blanking frequency as the reference. For further reduction of the switching transient, the blanker repetition frequency is chosen to be half of the switching frequency. Thus, the frequency components of the switching transient do not interfere with the EBIC signal.

By delaying the electron pulse with respect to the switching transient any phase of the switching event can be analyzed by means of EBIC. A computer controls the scan process and stores the measured data.

III. EXPERIMENTAL RESULTS

Using the above described setup a section of the 800-V diode was imaged by means of EBIC. The blanked electron beam with the duration of 100 ns was scanned over the area indicated on the schematic top view of a power diode in Fig. 2. The diode was provided with a single field ring, operating as edge termination.

Fig. 3 shows the current *I(t)* and voltage *V(t)* time series of a test diode under switching conditions. At $t = 0$ µs, it was turned off under zero current conditions to a reverse voltage of 500 V. At $t = 2$ µs, the diode was turned on to a forward current of 200 mA and after 5 µs it was turned off under hard switching conditions to a reverse voltage of 500 V. The low forward current was chosen, since a resistance connected in series with the diode was used to extract the small EBIC-signal with a sufficient signal-to-noise ratio. The commutation velocity *dI/dt* was chosen to be 20.8 A/µs, resulting in a peak reverse recovery current of 2.5 A, i.e. roughly one order of amplitude higher than the on-state forward current.

A set of EBIC maps at the times marked in Fig. 3 are depicted in Fig. 4. They illustrate how the space charge regions change during switching. During the first 1.5 µs (Fig. 4a) the diode voltage is -500 V and the EBIC map shows two ring-shaped regions with local maxima in the EBIC signal. They are located at the edge of the main *p* well (inner ring) and the field ring (outer ring) and indicate–as expected–a higher electric field strength in these regions due to the curvature of the *pn*-junction.

At $t = 2$ µs the diode was turned on and the space charge region started shrinking, as is visible by the decreasing signal in the field ring (Fig. 4b).

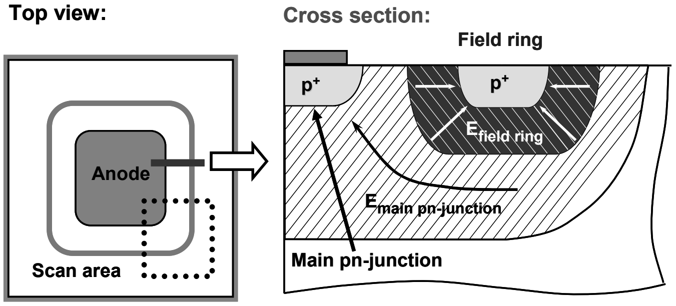

Fig. 2. Schematic view of the investigated power diode

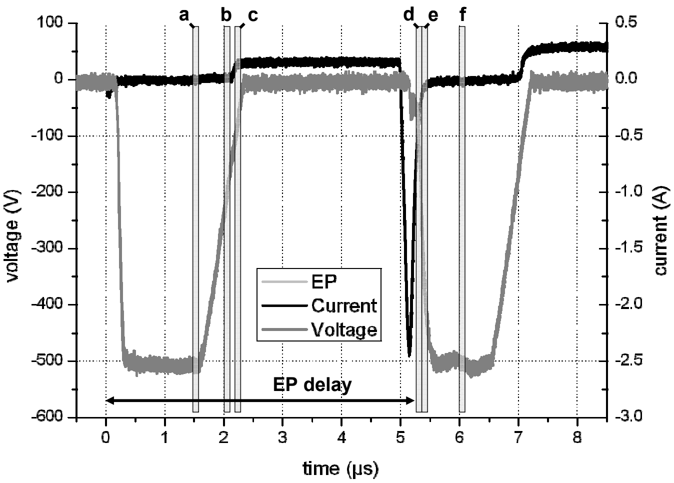

Fig. 3. Current and voltage time series in one of the branches of the Wheatstone bridge during switching of the diodes. Electron pulses EP show time point s of impinging electrons with the corresponding delay.

Finally, at $t = 2.2$ µs (Fig. 4c), the diode was in the on-state and the contrast in the EBIC signal was drastically reduced since the electric field in the diode is very weak under these conditions. After the diode has been turned off ($t = 5$ µs), the charge carriers were extracted from the bulk and the space charge region started to expand ($t = 5$ µs–6 µs, Fig. 4d-f). It is remarkable that the EBIC signal at the field ring is temporarily (e.g., at $t = 2$ µs, Fig. 4b and $t = 5.3$ µs, Fig. 4d) higher compared to the signal at the edge of the *p* well, indicating a higher electric field strength at the semiconductor surface of the field ring.

This effect and the overall diode behavior are better visible in Fig. 5, in which line scans obtained at the diagonal of Fig. 4 are plotted as a function of the electron pulse delay.

Another set of EBIC-maps shown in Fig. 6 was generated at the dynamically biased diode for four reverse bias voltages between 100 V and 800 V. Thereby the EBIC-maps were recorded at the time points $t = 5.5$ µs and $t = 6.6$ µs. It is worth noting, that the space charge region at the end phase of the reverse recovery period ($t = 5.5$ µs) is more extended than under quasi-static conditions ($t = 6.6$ µs). Furthermore, the EBIC-signal in the field ring exhibits two maxima at $t = 5.5$ µs–the moment close to the end of the reverse recovery phase–for the case that a reverse bias voltage of 800 V was applied to the diode. These peculiarities are possibly caused by hole currents flowing along the surface during the turn-off period. This assumption, however, has to be confirmed by additional investigations.

Comparing the maps for the applied reverse voltage of 100 V and 800 V, it is remarkable that the EBIC-signal at the lower voltage is higher compared to the case with the higher applied reverse voltage. A possible reason for this can be the smaller extent of the space charge, which collects the electron beam induced charge carriers very efficiently within the diffusion length of the free charge carriers.

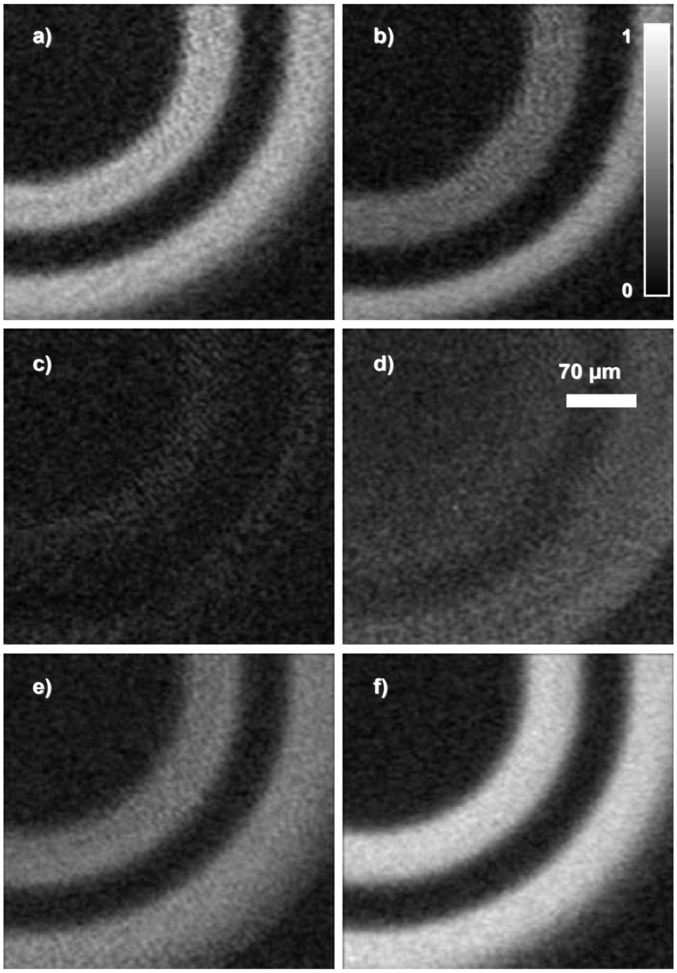

Fig. 4. EBIC maps of a power diode for different phases during the switching event. EBIC amplitude is in arbitrary units.

With increasing blocking voltage, the space charge region extends further, resulting in a broader distribution of the EBIC signal with lower intensity in the case of the lower applied reverse voltage. Device simulations are in preparation to confirm this interpretation.

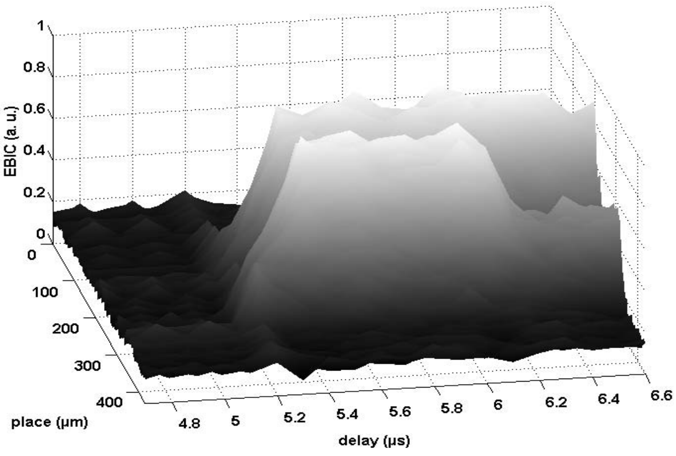

Fig. 5. Line scans through the EBIC-maps during the reverse recovery Period shown in Fig. 4 (arbitrary units)

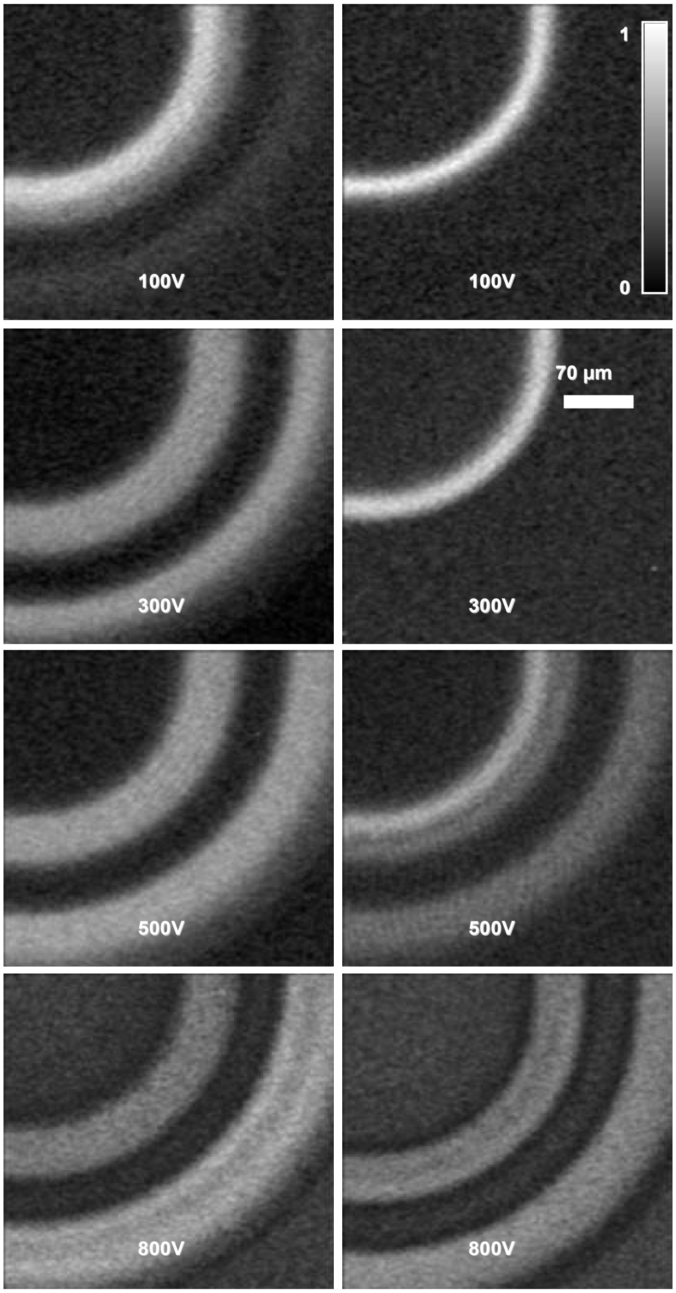

Fig. 6. EBIC maps of an 800-V diode for different reverse voltages and delays (compare Fig. 3). The left and the right column refer to 5.5 µs and 6.6 µs dalay of the electron pulse. EBIC amplitude is in arbitrary units.

An analogous behavior was observed by EBIC measurements on the statically reverse biased diode (Fig. 7). Since the spatial resolution (due to lower electron energy of 20 keV) and the signal-to-noise ratio were much higher for static measurements, the EBIC signal provides more details of the electric field distribution in the scanned area. For a reverse voltage of 850 V, a field enhancement occurs at the inner edge of the main *pn*-junction. For reverse voltages less than 500 V the EBIC-maps recorded under static bias conditions are similar to that recorded in the quasi-static case at $t = 6.6$ µs ensuing the reverse recovery phase (Fig. 6).

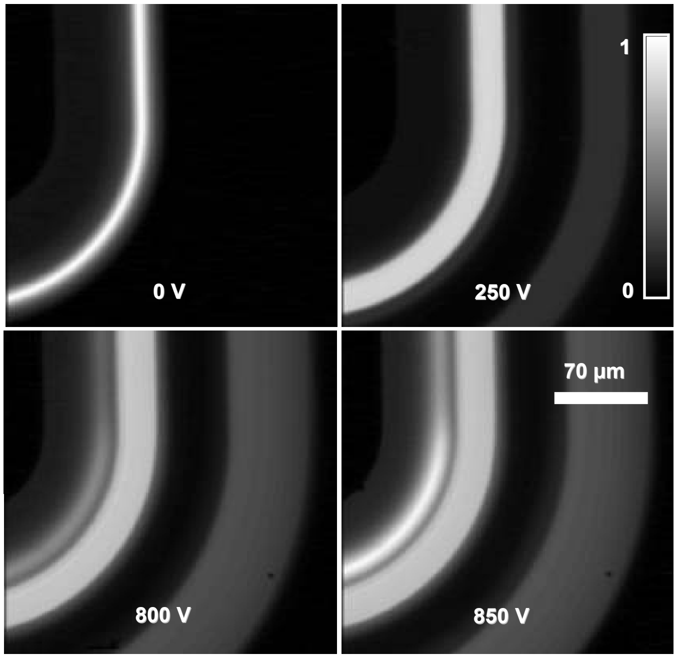

Fig. 7. EBIC maps of the 800-V diode under static conditions for four different applied reverse voltages. EBIC amplitude is in arbitrary units.

IV. CONCLUSION

In conclusion we point out that time-resolved EBIC-measurements based on a Wheatstone bridge and combined with lock-in technique provide a valuable tool for monitoring the dynamical behavior of the electric field distribution in the edge region of high-power devices. Reverse and forward recoveries of our 800-V test diode were imaged with a time resolution of 100 ns.

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