TCAD Simulations Combined with Free Carrier Absorption Experiments Revealing the Physical Nature of Hydrogen-Related Donors in IGBTs

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***Abstract*— Hydrogen-related donors can be advantageously used in IGBTs and power diodes with a view to creating field-stop layers and to optimising the electrical performance. In this work, the influence of hydrogen-related donors on the on-state plasma profile in field-stop IGBTs is analysed by means of free-carrier absorption measurements. For these investigations, dedicated IGBT test structures were used, which had been adapted to the specific properties of the employed measurement set-up. Two different hydrogen-related donor profiles were implanted into these IGBT samples and, subsequently, measurements with different current densities were compared to 2D TCAD numerical simulations. In the next step, the simulation models were adjusted, with respect to carrier lifetime and mobility to reflect the impact of a possible variation of these properties.**

Keywords— ***IGBT, Free Carrier Absorption Measurements, Proton Induced Donors, Carrier Lifetime, Carrier Mobility***

I. Introduction

The profound knowledge and understanding of the internal electronic behaviour of semiconductor power devices under specific operating conditions constitutes an indispensable prerequisite for their proper design and efficient device optimisation. Usually, such devices are characterised by electrical measurements resulting in the terminal behaviour of the device, while their local internal behaviour is not easily accessible by measurements. In order to enhance the accuracy and prediction of the applied simulation models, numerical analysis has to be supported by appropriate characterisation and model parameter extraction. To this end, a dedicated free-carrier absorption (FCA) measurement technique for the experimental analysis of the internal spatial- and time-resolved excess charge-carrier density distribution in vertical semiconductor power devices is employed by exploiting the plasma-optical effect [1]. In the present work, this technique is used for investigating the impact of hydrogen-related donors (HD) on the stationary excess charge-carrier density profile in IGBTs. HDs, generated in silicon devices by proton implantation, exhibit two major advantages: the low thermal budget [2] necessary for their creation, and the broad range of penetration depth which is beneficial for realising donor profiles acting as field stop (FS) layers in semiconductor power devices [3]. However, the quantitative analysis of microscopic physical properties such as carrier lifetime and mobility, which are necessarily needed to predict the electronic transport properties of these devices, is still problematic. Combining the data extracted by FCA measurements with a dedicated simulation and parameter extraction scheme enables the proper and accurate calibration of the transport models and, hence, the reliable design and efficient optimisation of HD-based devices by predictive TCAD simulations. Three IGBT structures, one reference sample without and two samples with implanted HD profiles, have been investigated by optical FCA as well as by standard electrical measurements (stationary transfer characteristics, dynamic turn-off) at room temperature and at 150°C. In order to assure an optimum interaction of the probing beam with the charge carriers inside the DUT and to ascertain that the disturbance of the probing beam by reflection from the contact edges is minimal, the peaks of the HD profile have been placed in the middle of the device (Fig.1).

A 2D simulation model (Fig.2) serves as basis for the interpretation of the measured data following an iterative inverse modelling procedure, which, in a first calibration step, is applied to the reference sample in order to minimise parasitic effects of the measurement set-up (e.g., parasitic capacitances) and to extract device-specific effects like oxide charges and contact resistances. The calibrated simulation model is applied for investigating the influence of HDs on the FS DUTs and the assessment of the related transport coefficients.

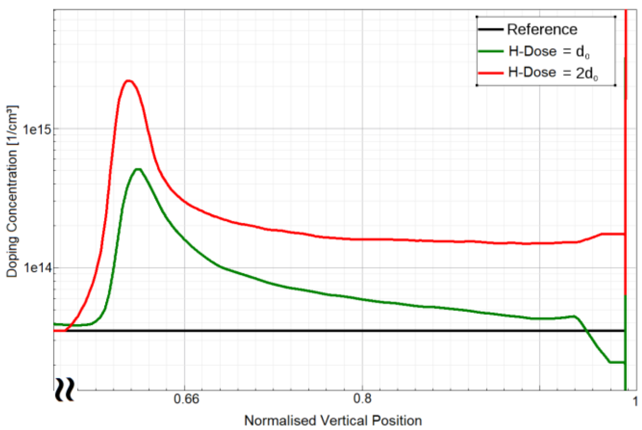

Fig. 1: Implanted hydrogen donor profiles and background doping of the reference device obtained from spreading resistance measurements.

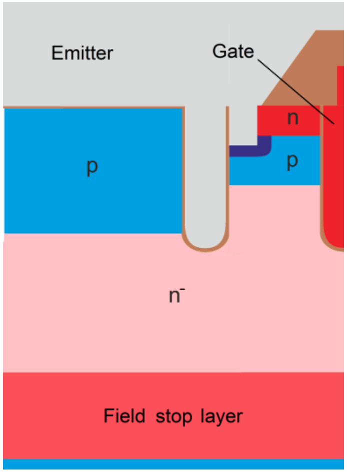

Fig. 2: Two-dimensional TCAD model of the IGBT trench cell under test.

II. Free-Carrier Absorption Measurement Technique

The applied FCA measurement technique exploits the plasma-optical effect [1], which describes the attenuation and deflection of an electromagnetic wave propagating through the interior of the DUT. The experimental set-up comprises a nearly incoherent light beam generated by an amplified-spontaneous-emission light source which is focused onto the centre of the DUT along the direction of the probing beam, while the device is subjected to periodic electric current pulses. The light beam traverses the DUT in lateral direction at a vertical position x through the drift region (Fig.3). In order to avoid free electron-hole pair generation by photons, a wavelength of $\lambda = 1550nm$ is used for the probing beam to ensure that the energy of the impinging photons is lower than the width of the silicon band gap ($E_{photon} < E_{gap}$). The nearly negligible optical transitions of electrons from the valence band to the conduction band do not significantly contribute to the total carrier concentration, also in consequence of the high density of electron states near the band edges [4]. The injection of charge-carriers in the active region of the DUT causes an attenuation of the propagating light beam, resulting in a reduction of the intensity of the transmitted light, which in turn is detected by a photo-diode. A basic sketch illustrating the orientation and location of the propagating light beam with respect to the DUT is shown in Figure 3.

The dominant processes that affect the optical absorption inside a semiconductor are band-to-band absorption (interband transition) and free-carrier absorption (intraband transition) [5]. Since the energy of the photons in the light beam is lower than the band-gap of silicon, the modulation of the light absorption coefficient α originates primarily from the rise of the free-carrier absorption caused by high injection of charge-carriers into the intrinsic region of the forward-biased IGBT. The high injection leads to a quasi-neutral electron-hole plasma ($n(x) \approx p(x)$) and, hence, α becomes proportional to the sum of the electron and hole density [1]. Therefore, the resulting modulation of the electromagnetic infrared wave gives an image of the local time- and position-dependent excess charge-carrier density $\Delta C(x,z,t)$, which can be extracted from the measured transmitted light intensity profile by exploiting the Beer-Lambert law:

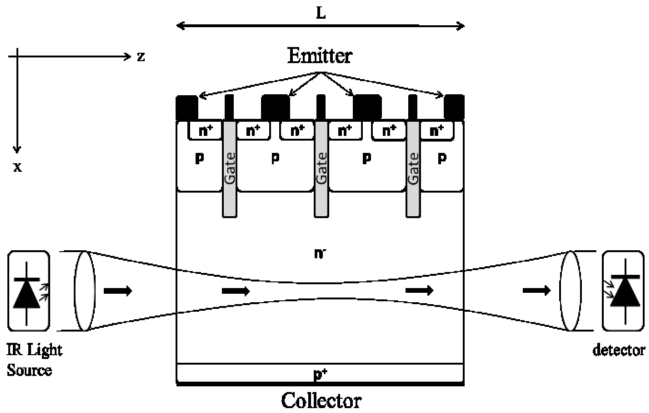

Fig. 3: Schematic drawing of the optical beam path in free-carrier absorption experiments.

$$I_{on}(x,t) = I_{off}(x) \exp\left[-\frac{\partial \alpha}{\partial C}\int_0^L \Delta C(x,z,t)dz\right] \quad (1)$$

Here I_{on} and I_{off} are the light intensities during the on-state and the off-state of the current pulse, respectively, and the z-integral extends in lateral direction along the optical path with interaction length L.

III. Measurement & Numerical Results

In the TCAD simulations, the field-stop profiles shown in Fig. 1 were used. For both the donor profile extracted from spreading resistance profiling (SRP) and the donor parameters in the TCAD model the well-known electrical properties of phosphorous doping were assumed.

Assuming quasi-stationary conditions during the on-state and during the off-state of the IGBT ($\partial/\partial t=0$) and quasi-1D current flow in vertical (x-)direction with negligible carrier recombination, the carrier balance equations for electrons and holes simplify to

$$0 = \operatorname{div} \vec{j}_\alpha = \frac{d}{dx} j_\alpha(x) \approx -\frac{d}{dx}\left(D_\alpha \frac{d}{dx} c_\alpha(x)\right) \text{ for } \alpha=n,p \quad (2)$$

where $c_n(x) = n(x)$ and $c_p(x) = p(x)$, respectively, and D_α denote the carrier diffusion coefficients. Consequently, we find

$$\frac{dn}{dx} = const., \quad \frac{dp}{dx} = const. \quad (3)$$

in the intrinsic region flooded by the electron-hole plasma and, hence, we obtain linear carrier density profiles as a result. This explains the shape of the measured and simulated carrier profiles inside the reference DUT (Fig. 4) for nominal current and one tenth of it at room temperature and at 150°C, respectively.

Simulations of the transfer characteristics (Fig.5) provided the basis for adjusting the density of oxide charges and the contact resistance. While the oxide charges affect the threshold voltage of the IGBT, the adjustment of the contact resistance has an impact on the slope of the transfer characteristics. In this way, the charge carrier density at the emitter side is controlled and can be adjusted in such a way that it corresponds to the data extracted from the FCA measurements.

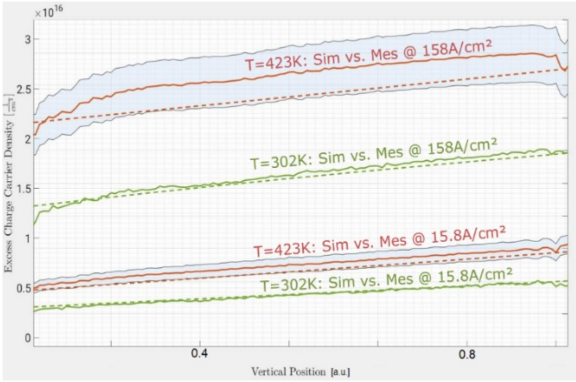

Fig. 4: Measured (solid) and simulated (dashed) excess charge carrier profiles in the reference DUT at room temperature (green) and 150°C (red).

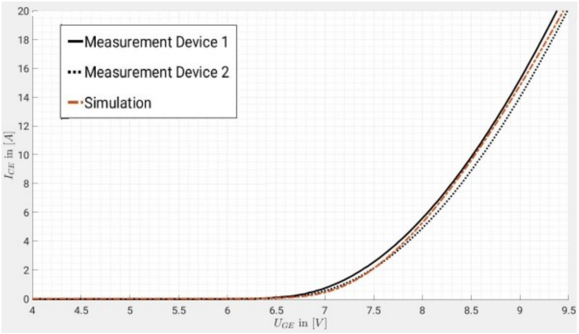

Fig. 5: Measured and calibrated simulated transfer characteristic as obtained after adjusting the density of oxide charges and the contact resistance.

The calibrated excess charge carrier profiles shown in Fig.4 have been used as initial values for simulating the turn-off transients of a double pulse test. The gradient of the calculated voltage transient dU/dt as well as the current transient dI/dt are in very good agreement with the measured turn-off transients, for room temperature (Fig.6) and for 150°C (Fig.7). This corroborates that the measured excess charge carrier gradient and the absolute values have been extracted very accurately by the FCA experiments.

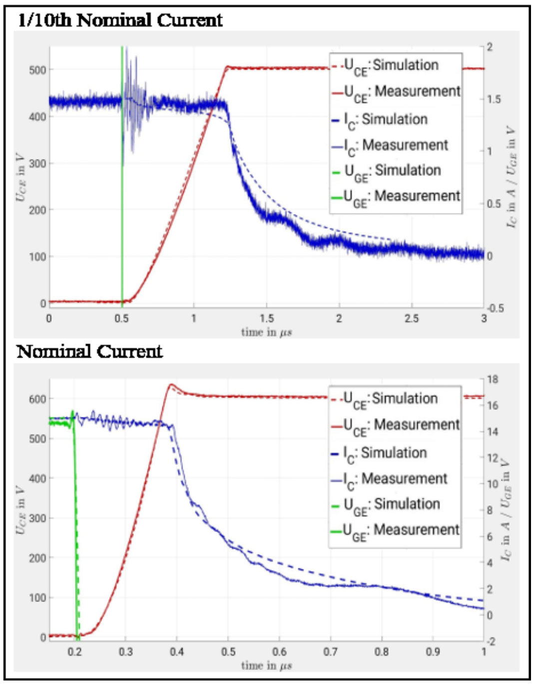

Fig. 6: Comparison of simulated and measured turn-off transients of the reference DUT at room temperature.

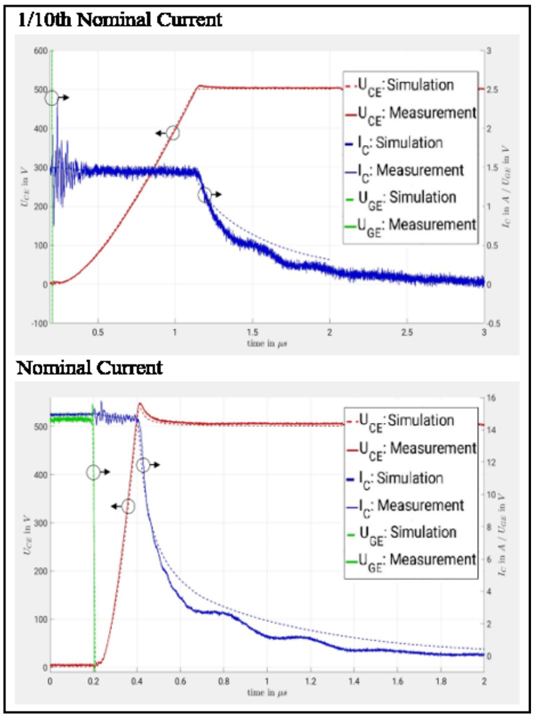

Fig. 7: Comparison of simulated and measured turn-off transients of the reference DUT at T=150°C.

The optically measured excess charge-carrier density profiles of the two IGBTs with FS layers (Fig.8) differ significantly from the linear profiles of the reference DUT without any FS profile (Fig.4) for the same terminal currents The excess charge carrier gradient along the FS profile is steepening with increasing proton dose. Inverse simulations reveal that the gradient of the excess charge carrier profile can be attributed either to a lifetime reduction in vicinity to the proton peak concentration or to a local reduction of the carrier mobility along the implantation path.

In order to model the reduction of carrier lifetime around the doping concentration peak of the HDs, the SRP doping profile is translated into a charge carrier lifetime profile τ(x) (Fig.9) with the relation:

$$\tau = 1/(c_{fact} N_{D,SRP}) \qquad (6)$$

where the factor c_{fact} is a fit parameter. Consequently, the carrier lifetime will locally degrade very steeply due to the high donor concentration N_D and rises again, beyond the donor peak, up to several µs. This δ-pulse formed lifetime profile produces the observed charge carrier gradient, which can be controlled by the factor c_{fact} in such a way that the

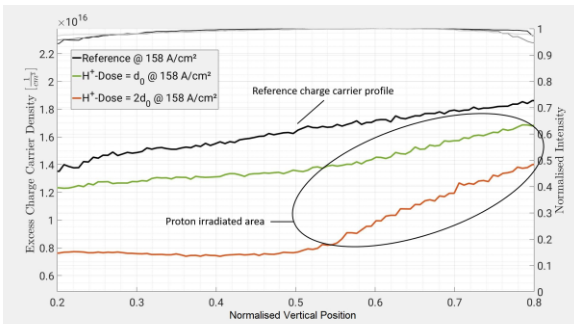

Fig. 8: FCA measurements at room temperature on the FS DUTs reveal that the charge carrier gradient along the implantation path becomes steeper with increasing hydrogen implantation dose.

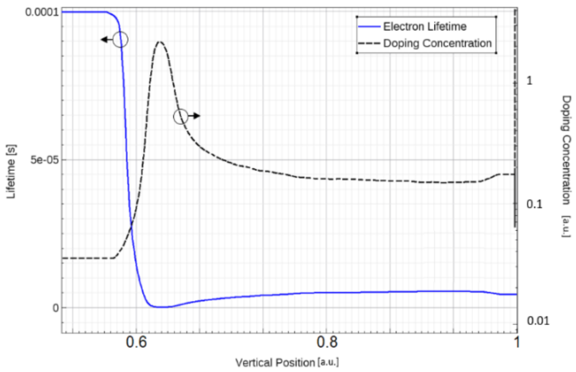

Fig. 9: Carrier lifetime profile (blue) as used for simulation. it has been generated on the basis of spreading resistance measurements of the doping concentration and the relation $\tau = 1/(c_{fact} \cdot N_{D,SRP})$.

simulated excess charge carrier gradient will match the simulated one. In the case of the DUT with the lower HD dose, the lifetime in the doping concentration peak decreases to 0.5µs.

It has been shown in [6] that the excess charge carrier gradient may also be affected by a reduction of the hole mobility μ_h. In order to generate the measured charge carrier gradient of the DUT with the lower HD dose, a reduction of the hole mobility by 5% along the implantation path is required (Fig.10).

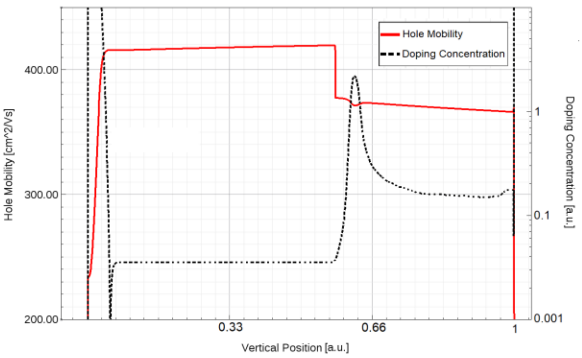

Fig. 10: Hole mobility profile (red) as used for simuation. The mobility along the implantation path is reduced by 5%.

Implementing either the lifetime profile or the local reduction of the hole mobility in the simulation allows us to adjust the carrier transport model in such a way that the measured excess charge carrier profile (Fig.11) is correctly reproduced. The relative deviation of the calibrated profiles and the measured ones is below 10% along the whole profile.

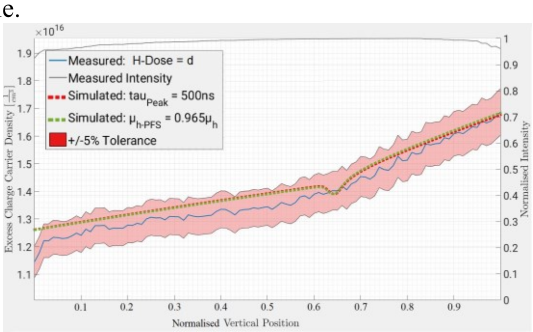

Fig. 11: Measured excess charge carrier density compared to simulations with adjusted model parameter for room temperature.

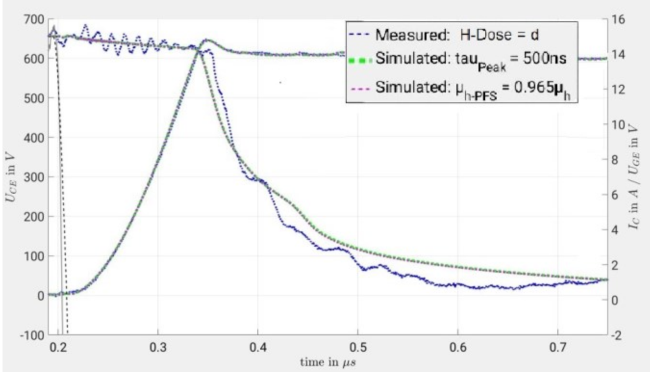

Fig. 12: Comparison of the two simulated turn-pff transients based on adjusted empirical models and the measured turn-off transients of the FS devices at room temperature.

The calibrated excess charge carrier profiles obtained from the FS samples (Fig.11) are used again as initial values for simulating the turn-off transients. The comparison of the data acquired from the double pulse test and with each of the two alternative simulation models shows that the hole mobility reduction as well as the reduced lifetime profile yield turn-off transients that conform very well with the measured data as long as the calibrated simulated excess charge carrier profiles concur to the measured ones (Fig.12).

IV. Conclusion

We have shown that the FCA measurement method is well suited for extracting excess charge carrier profiles in IGBTs. Furthermore, it allows for the investigation of additional FS layers which are created by proton implantation. Combining the results extracted from FCA analysis with an inverse modelling technique enables the calibration of the transport models for field stop devices. Our study reveals that a local reduction of the lifetime around the peak of the HD concentration as well as a reduction of the hole mobility along the implantation path can explain the experimental findings. Each of the two effects may be accounted for the good agreement between the experimental and simulated data, as long as the simulated excess charge carrier profiles are calibrated in such a way that they concur with the profiles extracted by the applied FCA experiments.

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