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A Physics-Based Model for Fast Recovery Diodes with Lifetime Control and Emitter Efficiency Reduction

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Abstract**—**This paper presents a physics-based model for the high-voltage fast recovery diodes. The model provides a good trade-off between reverse recovery time and forward voltage drop realized through a combination of lifetime control and emitter efficiency reduction techniques. The minority carrier lifetime can be extracted from the reverse recovery transient response and forward characteristics. This paper also shows that decreasing the amount of the excess carriers stored in the drift region will result in softer characteristics which can be achieved using a lower doping level. The developed model is verified by experiment and the measurement data agrees well with the model.

Keywords**—**Emitter efficiency, lifetime control, P-i-N diode, physics-based model

I. Introduction

THE high-voltage fast recovery diode (FRD) is one of the most important elements of the power electronics circuits. The most significant demands imposed on fast power diodes are short reverse recovery time together with low operating power dissipation (lower forward voltage drop) and high breakdown voltage. Also, the reverse recovery softness S is very important to avoid oscillations in circuit which can be destructive under certain conditions.

Nowadays, it is generally recognized that the most challenging task for the FRD performance improvement is the appropriate design of the trade-off between forward voltage drop and reverse transient characteristics. This trade-off is dependent upon a number of factors such as the epilayer width, the distribution of the deep level impurities, the doping profile and so on. Among these factors, lifetime (τ) is the most critical parameter for device characteristics. Many techniques of lifetime control have been developed to reduce the lifetime in the drift region to increase the switching speed or reduce the on state losses. The often used methods include the noble metal diffusion (gold or platinum) [1] and ion irradiation (helium or protons) [2]. Also, the recovery behavior of FRD can be improved by adjusting the efficiency of the emitters (anode emitter usually). Various concepts to reduce the anode emitter efficiency have been suggested and investigated in the past. For example, the merged pin/Schottky (MPS) diode in [3], the self-adjusting p-emitter diode (SPEED) in [4]–[5] and the hybrid diode in [6], the main idea of these concepts is to reduce the amount of carriers injected on the anode side for a better device behavior.This paper presents a physics-based FRD model which combines lifetime control with emitter efficiency reduction by means of reducing the emitter doping. The model could accurately predict both forward drop and reverse recovery switching characteristics. The excess minority carrier distribution during reverse recovery is analyzed to get a soft recovery performance. By simulating the turn-off transient response of a p-i-n diode, the minority carrier lifetime can be extracted. The physics-based rectifier model is developed in the Medici device simulator and the Tsuprem4 semiconductor process simulator realizing the physical, electrical and mixed-mode simulation.

The paper is organized as follows: Section II describe the diode design and the test circuit used for the simulation. Section III depicts the simulation model with lifetime control and emitter efficiency reduction while the validation for the FRD model with experiment data is presented in Section IV.

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II. Diode Simulation Model

A. Diode Structure

The analyzed device used in the modeling and characterization study is a planar fast recovery diode with reverse breakdown voltage as high as 1700V. The starting material is 85Ω·cm <111> oriented N-type float zone silicon. The vertical structure is the traditional $P^+N^-N^+$ structure with the N^--layer and N^+-layer are created by diffusion. The width of N^- drift region is about 175μm. The peak concentration of backside diffused N^+ region is about 1×10^{20} cm^{-3} with a diffusion transition region of approximately 80 μm. The P^+ emitter doping level at the anode contact is set 1×10^{18} cm^{-3} as a reference. The depth of the pn junction is about 8um. The effective area of the diode is set at 50 cm^2 to achieve a rated forward current of 100A.

The 1700V reverse breakdown voltage is achieved by utilizing a multiple field limiting ring edge termination coupled with high resistivity poly-silicon floating field plate. The floating field ring which can be fabricated in a single mask step together with the P^+-type anode layer is used for improving the breakdown voltage. The field plates are designed to extend over the space between the junctions. The field plates reduce the electric field at the edges of all the junctions and also prevent mobile ions from entering the field oxide. A cross section of the device is shown in Fig. 1. The doping profile is shown in Fig. 2.

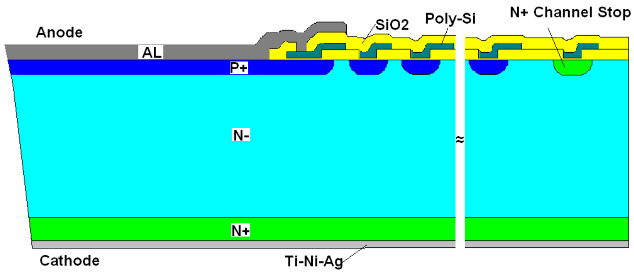


Fig. 1 Cross-section of the fast recovery diode

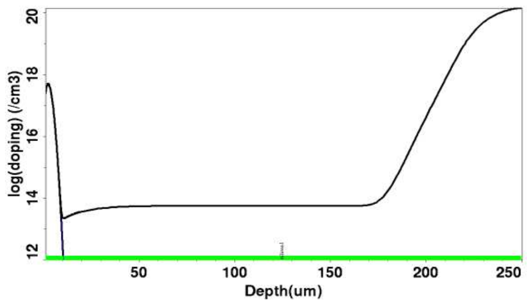


Fig. 2 Doping pro files of the diode structure from anode's surface

B. Test Circuit

In order to analyze the diode reverse recovery characteristics, a ramp RL test circuit is used to simulate the transient response as shown in Fig.3 [7]. This circuit model is adequate for investigating the diode reverse recovery characteristics. It retains the essential features of inductive switching behavior.

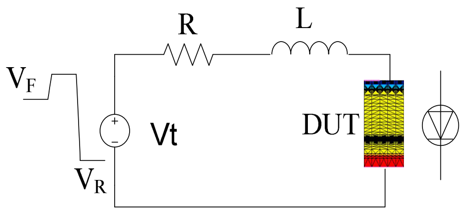


Fig. 3 Schematic of reverse recovery circuit used in the mixed-mode simulation

The applied voltage is set by a time dependent voltage source through a piecewise linear function. The known forward current I_F through the DUT, must flow for a sufficient period of time allowing the diode to reach its stable conduction state. I_F can be adjusted by the resistor R. The circuit inductance L_C is given a value of 0.3uH, while R_C had a value of 0.1Ω. The diode conducted a forward current of 1A which is then ramped by the application of a reverse voltage of 30V. The commutating di/dt is controlled via the circuit inductance L and the applied reverse voltage V_R, therefore di/dt is equal to 100A/us.

III. Simulation Model Development

In order to analyze both static and dynamic characteristics of all structures, two-dimensional device simulator Medici is used after a satisfactorily results from the technological simulation following by the generation of device structure using the process simulator Tsuprem4. The numerical analysis is carried out using the Newton method by solving the Poisson and continuity equations.During the simulation, different Medici physical models have been used in addition to the default models to accurately predict the device characteristics. Thus, it allows take into account concentration and high electric-field dependent mobility as well as general model for degradation of mobility with transverse electric field applying all over the device not just at surface. Carrier-carrier scattering is included to account for ambipolar transport effects. Recombination mechanisms include Auger recombination and the Shockley-Read-Hall (SRH) recombination process with doping dependent lifetime and a single recombination level in the center of the band gap. Bandgap narrowing as well as temperature dependent lifetime are taken into account in the simulation. The model used to simulate avalanche breakdown ionization for the reverse biased condition includes carrier generation due to impact ionization. Temperature operation is set at 298K (room temperature).

In order to obtain beneficial static characteristics and to optimize the dynamic diode behavior for both high di/dt and high dv/dt applications, two important approaches have been taken:

A) Lifetime control: adjusting the carrier lifetime in the drift-region of device
B) Emitter efficiency reduction: adjusting the efficiency of the emitters by their doping profile

A. Lifetime Control

The lifetime value of the carriers in the drift-region is one of the most important design parameters for a P-i-N diode. Reduction of on state losses or increasing of diode speed are achieved through modifications of carrier lifetime. The lifetime of the carriers can be extracted by simulating the reverse recovery and forward drop characteristics.In the simulation, the values of lifetime are set at 50ns, 300ns, 500ns, 1us.The test circuit conditions for the reverse recovery characteristics are kept at the reference values: V_R=30V, di/dt=100A/us, I_F=1A.The reverse recovery waveforms of the FRD with different lifetime values are shown in Fig. 4. The FRD model predicts that the reverse recovery time (t_{rr}) decreases gradually when the lifetime is reduced. However, lower lifetime values results in a harder “snappy” recovery with oscillations, caused by sudden disappearance of minority carriers stored in the drift-region. Also, the increase of peak reverse current as lifetime increases can be clearly observed. The voltage waveforms of the forward drop predicted by the model with variable lifetime values are shown in Fig. 5. It can be seen that, the forward drop of the FRD increases steeply as the lifetime decreases from 1us to 50ns. This means the current density of the FRD decreases when the lifetime increases. A trade-off between the switching speed and the forward voltage drop is observed, as expected.

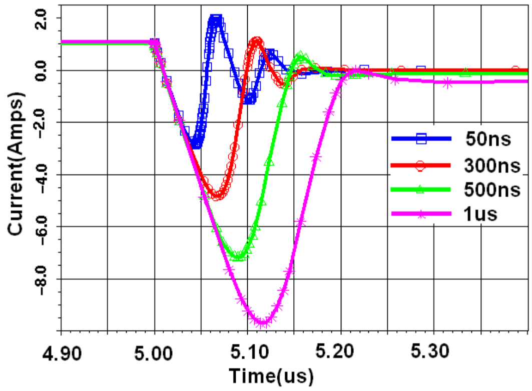


Fig. 4 Reverse recovery waveforms for various values of lifetime: 50ns, 300ns 500ns 1us

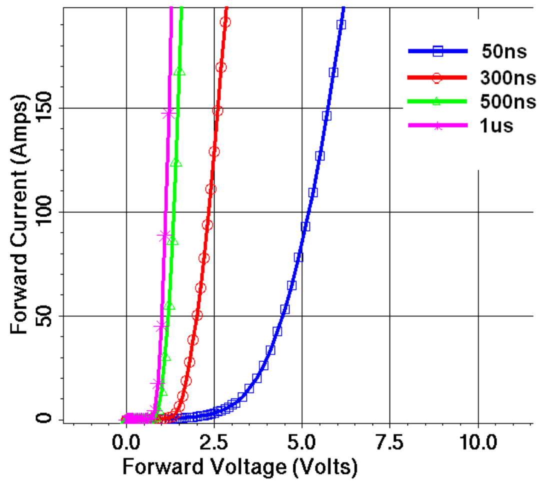


Fig. 5 Forward voltage drop waveforms for various values of lifetime: 50ns, 300ns 500ns 1us

A way to verify that the diode has the right lifetime value is to try to match both reverse recovery and forward characteristics using the lifetime model. From the simulation above, low forward voltage demands the value of carrier lifetime as high as possible while high switching speed needs lifetime value stay at a low level. Therefore, the lifetime is chosen by the demand of the device performance (V_F, t_{rr}, S etc.). Considering the commercial high-voltage FRD on the market, the forward voltage V_F for the 1700V/100A FRD simulation model should be less than 2.5V and the reverse recovery time t_{rr} should be less than 100ns at the test condition of I_F=1A. The simulation results of the reverse recovery and forward characteristic for the model are shown in Table I. It can be seen that when the lifetime value is between 200ns and 250ns which can be achieved through a specific lifetime control process (platinum doping or electron irradiation), both the reverse recovery time and forward voltage meet the design requirement.

B. Emitter Efficiency Reduction

TABLE I
VF AND T_{RR} FOR DIFFERENT LIFETIME VALUES

τ (ns)	t_{rr} (ns)	V_F (volts)
150	82	3.2
200	88	2.3
250	93	2.1
300	110	1.7

In order to prevent the snappy recovery due to the low carrier lifetime, certain design consideration must be taken into account to minimize the effects of any current nonuniformities. Using emitter efficiency reduction techniques could achieve a desirable soft recovery performance. This improvement is due to the fact that the reduced carrier concentration in the drift-region takes to a faster extraction of the carriers during reverse recovery, which resulting in less reverse current peak and faster reverse recovery. It is desirable for the reduction of switching power losses. Actual devices tend to increase end region recombination effects, that is, to reduce end region emitter efficiency, since the increase of end region recombination results in an improvement of dynamic behavior [8]–[9].

Fig. 6 shows the reverse recovery current waveforms for the diode with different doping level. The lifetime is set at 250ns as simulated above while the other of the other parameters of the diode are kept at their reference values. As can be seen in Fig. 6, the value for the reverse recovery time increases from 81ns to 93ns to 101ns as the doping level increases from 1×10^{17} cm^{-3} to 1×10^{18} cm^{-3} to 1×10^{19} cm^{-3}, while the forward voltage stay around 2.2V with very little change as shown in Fig. 7. It is clear that snappiness occurs at higher doping levels, while a softer recovery occurs at lower levels. Obviously, lower emitter efficiency improves the reverse recovery characteristic greatly with a remarkable forward voltage performance.

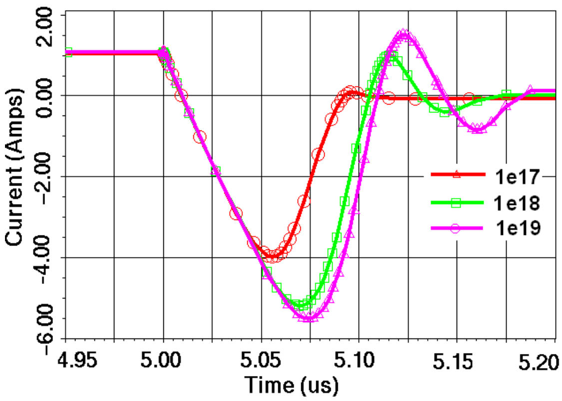


Fig. 6 Reverse recovery waveforms for the diode model with different doping level: 1×10^{17} cm^{-3}, 1×10^{18} cm^{-3}, 1×10^{19} cm^{-3}

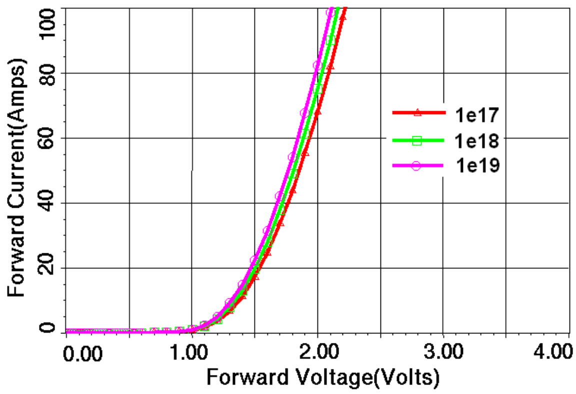
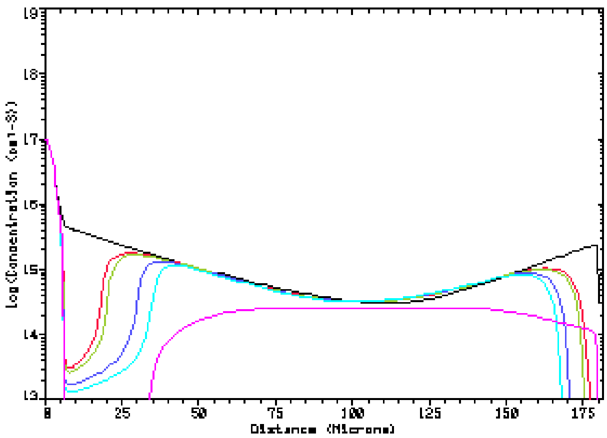
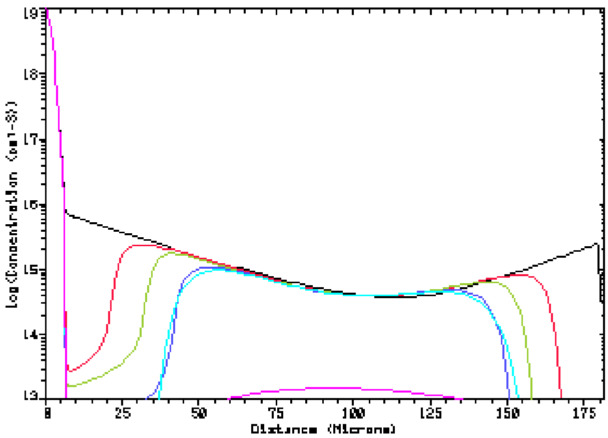


Fig. 7 Forward I-V curves of the diode model with different doping level: 1×10^{17} cm^{-3}, 1×10^{18} cm^{-3}, 1×10^{19} cm^{-3}



(a) Low P emitter doping (1×10^{17} cm^{-3})



(b) High p emitter doping (1×10^{19} cm^{-3})

Fig. 8 Excess minority carrier distribution during reverse recovery for different emitter doping level

Fig. 8 shows the excess minority distribution during reverse recovery transient with different emitter doping. A higher emitter doping level will result in a higher concentration of minority carriers stored near the P^+N^- junction than on the N^-N^+ side as shown in Fig. 8 (b). The total amount of stored charge is larger in this case, therefore a longer period is needed to clear the P^+N^- junction from these excess carriers, meanwhile this extra time will lead to an extra removal of carriers from the P^+N^- side, causing the depletion layer to build up on both ends. This will lead to the disappearance of charge near the N^-N^+ junction which is crucial for soft recovery characteristics of the diode. As can be seen in this case the amount of stored excess carriers is vital to determine whether the diode will be snappy or soft. A conclusion can be reached here that decreasing the amount of the excess carriers stored in the drift region from the P^+N^- junction to the N^-N^+ junction will result in softer characteristics, reducing the possibility of a space charge region building up at both ends.

IV. Model Validation

According the model simulated above, the FRD is fabricated using <111> oriented N-type float zone silicon. The lifetime control is implemented by platinum diffusion used to achieve the lifetime value obtained in the model. Some process parameters are extracted by the Tsuprem-4 process simulator, such as junction driven-in time, implanted dose and so on. In order to reduce the emitter efficiency, the doping level and the junction depth have to be reduced.

Fig. 9 shows the reverse recovery current waveforms for V_R=30V/I_F=1A operating conditions. As can be seen, the figure shows a very soft recovery characteristics and low peak reverse recovery current. The reverse recovery time t_{rr} of the experiment is 79ns while the t_{rr} of the simulation model is 82ns. The simulation results in Fig. 6 with 1×10^{17} cm^{-3} doping level and lifetime control show a good agreement in reverse recovery time t_{rr} and the softness S with the experimental data. The reverse recovery current I_{RR} of simulation is not equivalent to that of experimental data, since it is very difficult to incorporate all unknown circuit parasitic in the simulation. Fig. 10 displays the forward static characteristics of experimental FRD and the physics-based model. The simulated behavior of diode model closely matches that of the experimental measurements. It is shown that the FRD model proposed could accurately predict both forward drop and reverse recovery characteristics.

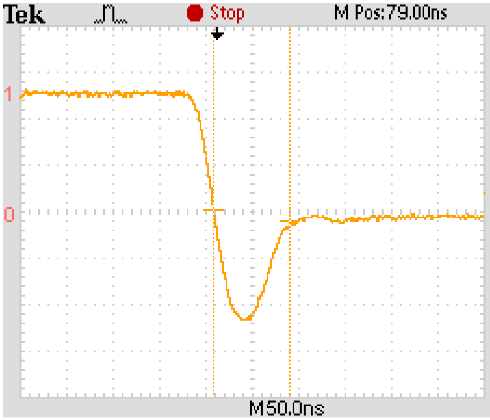


Fig. 9 Experimental reverse recovery waveform at di/dt=100A/us, I_F=1A, V_R=30V, (0.4A/div, 50ns/div)

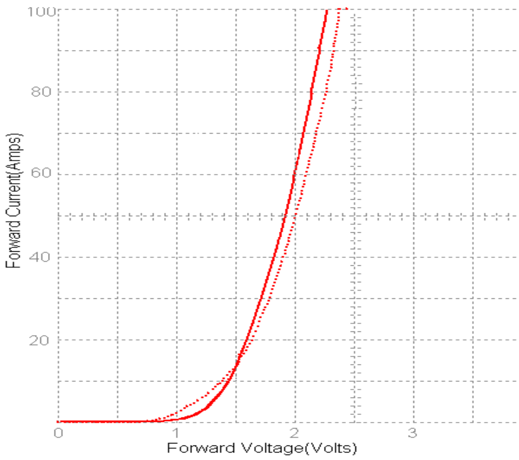


Fig. 10 Forward voltage drop for the FRD. Solid line: the simulation model; dotted line: experimental (10A/div,0.5V/div)

V. Conclusions

The physics-based fast recovery diode model has been successfully developed based on the physical process in the semiconductor device. In the model, a good trade-off between forward voltage drop and reverse transient characteristics is obtained result from the combination of lifetime control and emitter efficiency reduction techniques. A series of simulations is implemented in order to get a desirable match between the forward drop and the reverse recovery time. The model has been test for various operating conditions and a very close agreement is found between simulation and experimental data. Also, the excess carriers stored in the drift region are analyzed and a very soft recovery performance and low peak reverse recovery current are achieved in the reverse recovery characteristics.

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