# A Physics-Based Characterized Model for an Ultrafast Planar Rectifier

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***Abstract*–This paper presents a characterized model for an ultrafast-recovery (UFR) rectifier based on the manufacturing processes and device structural geometry. The accuracy of the developed model depends upon the proper selection of physical models and model parameters; especially carrier lifetime, which is a key parameter to the device characteristics. Different models and model parameters of the numerical device simulator are studied to realize a unique set of models that can accurately predict both static and dynamic characteristics of the rectifier. The developed model is verified through experimental data.***

## I. INTRODUCTION

The power rectifier is the most fundamental building block among all power semiconductor devices (PSDs). Without an accurate power rectifier model, accurate simulation results of any realistic power electronic circuit cannot be achieved. The representation of forward drop and reverse-recovery transient characteristics of the rectifier is the most challenging task while developing an accurate rectifier model. Several power rectifier models have been addressed to date. These models are classified as: (1) macro models which disregard the internal physical processes of the device and have a limited range of operation; (2) analytical models having empirical expressions which are characterized by difficult and tedious parameter extraction procedures. However, neither of these models can accurately predict both forward drop and reverse-recovery switching characteristics, simultaneously. Alternatively, numerical modeling, a complete physics-based modeling, has superior accuracy to the other modeling approaches, but tends to depend heavily on fabrication information associated with the device. Using confidential process and device information for the rectifier available through the manufacturer, the numerical device simulator, MEDICI® [1] is being utilized to realize an accurate power rectifier model which can exactly replicate the experimental data for both forward drop and reverse-recovery transient.

Besides the rectifier's process and device information, the accuracy of the model is enormously dependent on the MEDICI physical models and model parameters. Among these parameters, *lifetime* ($\tau$) is the most critical parameter and virtually controls the trade-off between forward drop and reverse transient characteristics. As with other power semiconductor devices, the lifetime of the rectifier becomes an unpredictable factor when power rectifiers are subject to "lifetime killing" to improve switching speed. However, it has been suggested in various literature [2]-[4] that the lifetime of the rectifier can be extracted from the measured ramp reverse-recovery current waveform.

A typical reverse-recovery current waveform is shown in Figure 1. The key parameters are $T_A$, $T_B$ and their associated parameter, $S = T_B/T_A$, which is referred to as the softness factor. Larger values of $S$ represent a "softer" recovery. Thus far, it has been shown that the $T_A$ portion of $T_{RR}$ is an inherent result of a rectifier's device characteristics, and can be used to compute the high-level recombination lifetime of the device. On the other hand, it is reported in [2, 4] and is also found in our experimental data, that the $T_B$ portion is not consistent and appears dependent upon the interaction of

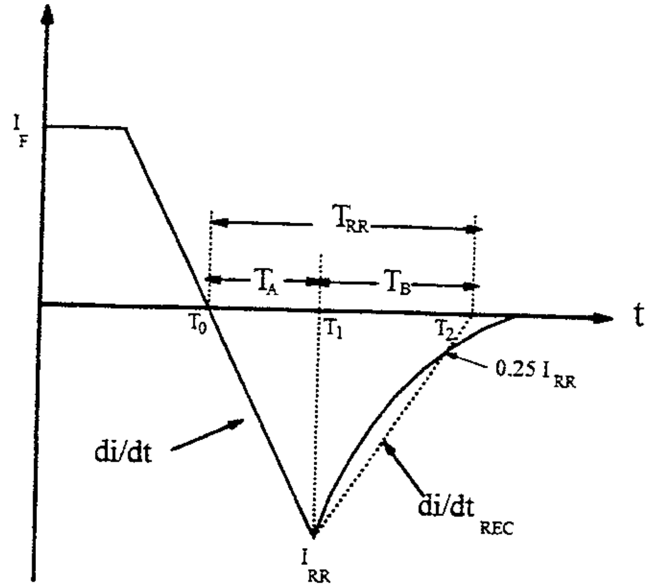

Figure 1: A typical reverse-recovery current waveform.

device characteristics, circuit layout, and circuit operating conditions.

As a result, it is assumed that if $T_B$ has anything to do with minority carriers, its effect must be second or third order. This implies that at time $T_1$, there are very few, if any, minority carriers that have not been either recombined or extracted [4]. It is therefore the purpose of this paper is to extract the lifetime from the $T_A$ measurement, and to use $T_A$ (termed hereafter as reverse-recovery time) as a comparison parameter instead of $T_{RR}$ ($T_{RR} = T_A + T_B$) for model validation. It is also the purpose of this paper to predict both forward drop and reverse-recovery current waveform using a single *lifetime* number and one set of models and model parameters.

## II. MODEL CALIBRATION PROCEDURE

The procedure to calibrate any model is called *Model Robustness Validation*. As applied to a semiconductor model, this means the methods to validate the accuracy of the process, device, and package simulation tools used to design semiconductors. This procedure is summarized in fifteen (15) steps below:

1. Select the process, device, and/or package to be simulated.
2. Select the output variables to be simulated at appropriate temperatures.
3. Obtain input variables information (e.g., epi specs, process recipes, mask layout, package layout).
4. Obtain measured data (e.g., $t_{ox}$, $R_s$, $x_j$, CD's, SRP's, BV, $R_{on}$, $t_s$ $\theta_{jc}$).
5. Obtain default models (set of physical models and coefficients initially used).
6. Run simulations using input information.
7. Compare simulation data to measured data and determine accuracy.
8. If model error meets acceptable limits, go to step 15 (acceptable customer limits should be documented in step 15)
9. Selection of which models to add, delete, or modify.
10. Design DOE of the model variables.
11. Simulate model DOE.
12. Select new models.
13. Re-run simulations and determine accuracy.
14. If model error is unacceptable, go to step 9 (intractable problems may require development of entirely new models).
15. Publish the calibrated simulation files(s), with accuracy comparisons to the measured data.

## III. ULTRAFAST PLANAR STRUCTURE

The device used in the modeling and characterization study was, as noted, a planar high voltage ultrafast P-i-N rectifier. The vertical structure consisted of an ion implanted $P^+$ (boron-doped) anode and $P^+$ rings diffused into an $N^-$ (phosphorous-doped) epitaxial layer. The substrate was an $N^{++}$ (arsenic-doped) with a <100> crystal orientation.

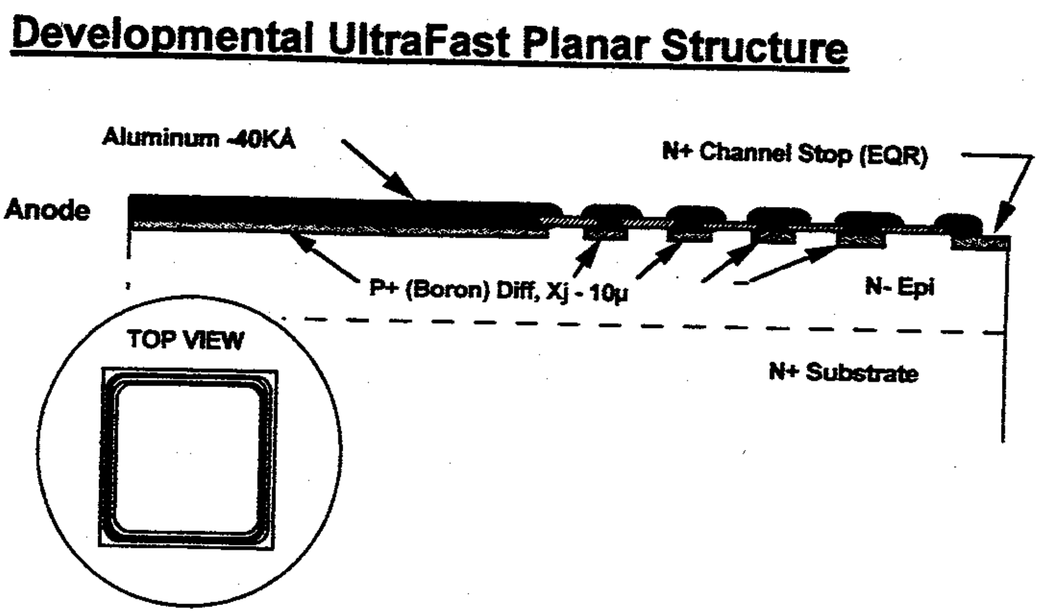

Figure 2: Device cross-section of an ultrafast planar rectifier.

The 1200 V reverse breakdown voltage was achieved by utilizing a multiple floating ring edge termination coupled with high resistivity epi of appropriate thickness. The forward voltage, $V_F$ is minimized through bipolar conductivity modulation of the epi region with hole injection from the anode. Carrier lifetime is minimized by a heavy metal (Pt) lifetime reduction process used to help the device to achieve its relatively low reverse-recovery switching time, $T_{RR}$. Figure 2 shows the representation of the developmental ultrafast planar structure.

## IV. LIFETIME MEASUREMENT

As reported in literature [2]-[4], the lifetime of the power rectifier can be extracted from the rectifier's reverse-recovery measurement. The rectifier chosen for this measurement is Motorola's developmental 1200V/15A ultrafast planar P-i-N structure. In Figure 3, a fixed ramp rate (*di/dt* ) of 100 A/µs is used; and $T_A$ is measured for various forward currents, $I_F$ from 1 to 18 A. In Figure 4, for a fixed forward current of 5 A, $T_A$ is measured for different current ramp rates, di/dt from 25 to 400 A/µs. The most impressive feature of these curves is that they show a plateau for $T_A$ of about 51 ns; which occurs at high $I_F$ and at low *di/dt* as shown in Figures 3 and 4. Surprisingly, this number turns out to be the minority-carrier high-level *lifetime* of the device [4]. This *lifetime* number has been analytically proved by Kao and Davis [2] under the assumption that there are no excess carriers at the conclusion of $T_A$ (i.e., $Q(T_1) = 0$ in Figure 1). It is found in our experiment that measured $T_A$ for different current and ramp rate conditions is an excellent agreement with the analytically calculated $T_A$ using the lifetime of 51 ns. However, this *lifetime* number may change slightly due to the change of forward current $I_F$. It is further reported in [3] that lifetime can also be calculated even with the inclusion of $T_B$ portion in the analysis. Using this analysis, the *lifetime* number computed from the experimental data varies from 70 ns to 200 ns, where $T_B$ is assumed to be non-zero. So, this *lifetime* number is not consistent and varies for a wide range for different operating conditions. This is due to the fact that $T_B$ itself is not consistent and extremely dependent upon circuit environment. Therefore, the assumption that

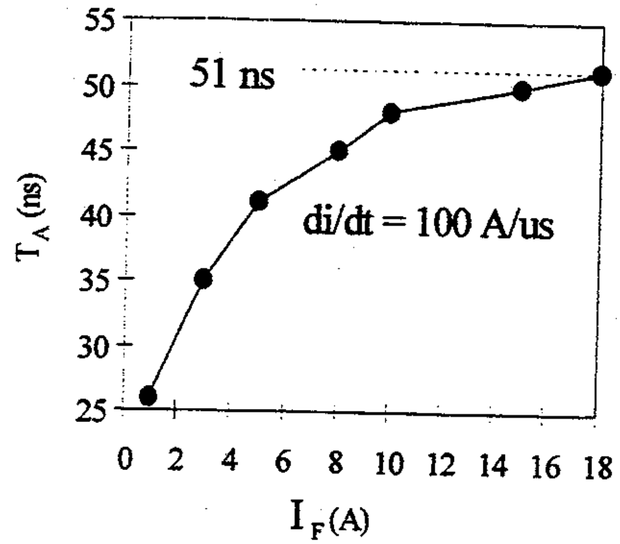

Figure 3: Curve for $T_A$ versus $I_F$ for a fixed ramp rate.

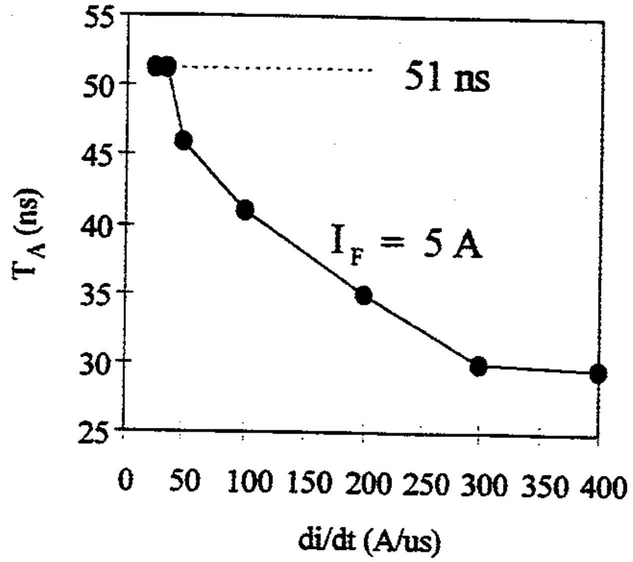

Figure 4: Curve for $T_A$ versus *di/dt* for a fixed forward current.

excess carrier concentration is negligible in the $T_B$ portion provides the robustness of lifetime calculation.

## V. SIMULATION MODEL DEVELOPMENT

The physics-based rectifier model is developed in the MEDICI device simulator using the numerical modeling approach. The objective of this modeling approach is to develop a rectifier model that can replicate the forward and the reverse-recovery characteristics for the same set of MEDICI models and model parameters. The rectifier reverse-recovery phenomenon is the most critical of the transient effects and must be modeled accurately. The reverse recovery occurs when the rectifier is turned-off rapidly from its on-state to the off-state. This effect is due to the charge that is accumulated during the forward conduction that must be removed from the drift region before its transition to the off-state. When the rectifier is switched off, the charges are removed from the drift region by recombination, diffusion and sweep-out actions [5].

In order to verify the rectifier's reverse-recovery characteristics, a MOSFET-based inductive switching test circuit similar to the experimental test setup is simulated as shown in Figure 5.

The basic rectifier model parameters can be derived from the device fabrication data, e.g., epi-specifications, process recipes, mask and package layout. Analytical doping profiles are used to match actual measured spreading resistance profiles (SRPs). The MEDICI physical models that are studied are concentration and electric-field dependent mobility, Shockley-Read-Hall (*SRH*) recombination with doping dependent lifetime, Auger recombination, and band-gap narrowing [1]. The initial simulation used the *PHILIPS* mobility model (with changed coefficients as suggested in the MEDICI manual), and the *SRH* recombination model with high-level lifetime (hole lifetime, $\tau_{po}$ + electron lifetime, $\tau_{no}$) of 51 ns as determined from the measured data. However, this *lifetime* number along with the default recombination model parameters cannot accurately predict both forward drop and reverse transient characteristics unless the recombination trap energy level for platinum is set to 0.17 eV above the valence band. That means, lifetime model parameter "ETRAP" in MEDICI is changed from 0 eV (default) to -0.38 eV (ETRAP = $E_t$ - $E_i$ = 0.17 eV - 0.55 eV). However, it is worth mentioning that same forward and reverse characteristics can also be achievable by increasing the

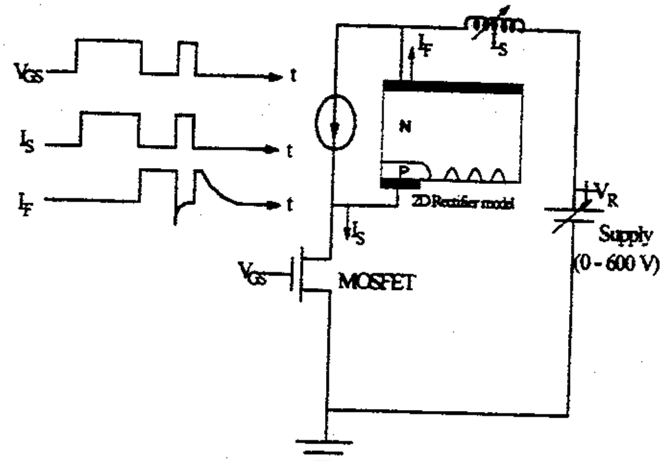

Figure 5: MEDICI simulation circuit.

high-level lifetime ($\tau = \tau_{po} + \tau_{no}$) to 160 ns from 51 ns with a default "ETRAP" = 0 eV. This implies that the effect of increasing the high-level lifetime to 160 ns with a default recombination trap level at mid-band gap is equivalent to a lifetime of 51 ns with a trap level near to the valence band. This physically proves that lifetime increases as the trap level is away from the midgap [6]. Further investigation is necessary to demonstrate the actual position of the recombination trap levels and their effects on the high-level lifetime.

## VI. RECTIFIER MODEL VALIDATION

The experiments and simulations are performed for different current, voltage and ramp rate conditions at room temperature (25°C). Figure 6 displays the rectifier forward drop for various current densities. The simulation results show good agreement with the experimental data. Figure 7 shows the trade-off curve of the forward drop, $V_F$ versus reverse-recovery time, $T_A$ determined by simulation with two experimental data points corresponding to two different lifetimes. The simulated trade-off curve (solid line) is produced for different lifetimes, with "ETRAP" = 0 eV.

The simulated reverse-recovery current waveforms for a wide range of forward currents, $I_F$ and ramp rates, $di/dt$ are compared with the experimental data. An excellent agreement in peak reverse-recovery current, $I_{RR}$ and the first portion of reverse-recovery time, $T_A$ is found for various forward current and ramp rate conditions. In simulation, the second portion of reverse-recovery time, $T_B$, is not always equivalent to that of experimental data, since it is very difficult to incorporate all unknown circuit parasitics in the simulation. As for demonstration, the experimental and simulated reverse-recovery current waveforms for 100 V/15 A operating conditions are shown in Figures 8 and 9.

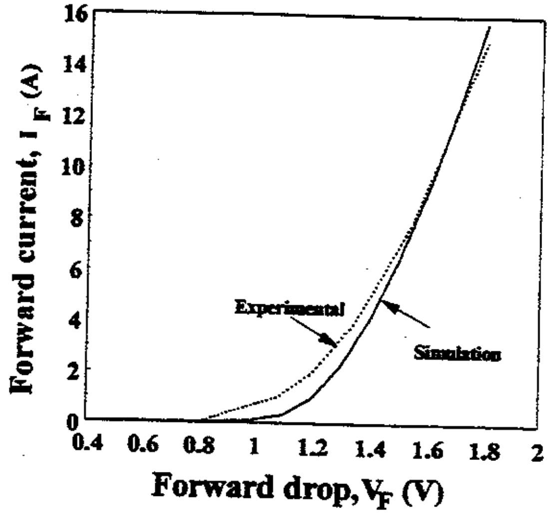

Figure 6: Forward drop of the power rectifier. Solid line: simulation; dotted-line: experimental.

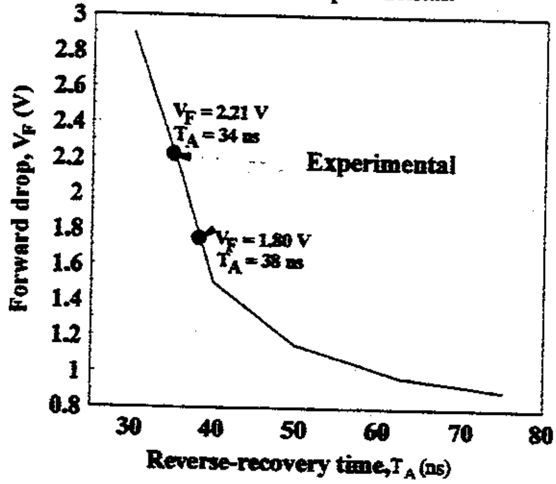

Figure 7: Trade-off curve of the forward drop and reverse-recovery time, $T_A$ versus high-level lifetime. Solid line: MEDICI model simulation; dot (top): experimental (at $V_R$ = 100 V, $I_F$ = 15 A, $di/dt$ = 425 A/μs), dot (bottom): experimental (at $V_R$ = 100 V, $I_F$ = 15 A, $di/dt$ = 425 A/μs).

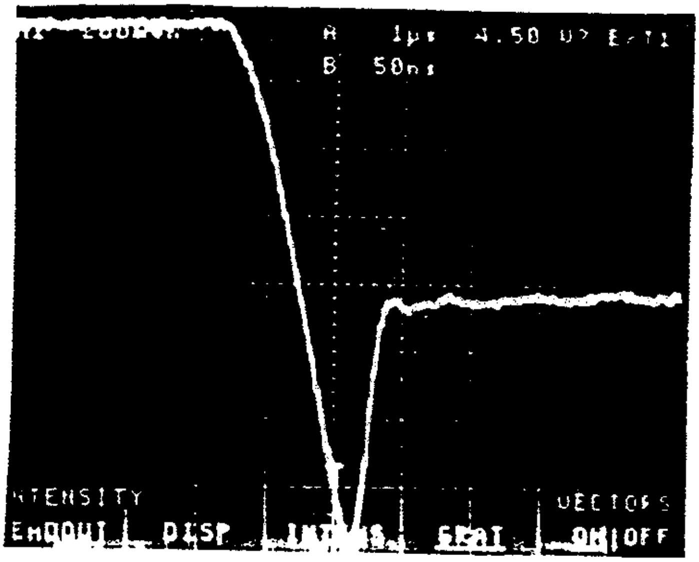

Figure 8: Experimental reverse-recovery current waveform (at $di/dt$ = 425 A/μs, $I_F$ = 15 A, $I_{RR}$ = 15.2 A, $T_A$ = 38 ns, $T_B$ = 31 ns).

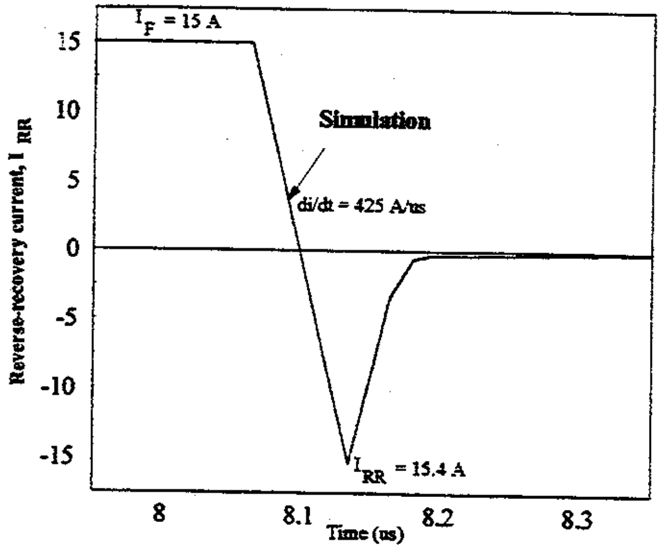

Figure 9: Simulated reverse-recovery current waveform (at $di/dt$ = 425 A/μs, $I_F$ = 15 A, $I_{RR}$ = 15.4 A, $T_A$ = 37 ns, $T_B$ = 33 ns).

## VII. CONCLUSIONS

The physics-based power rectifier model has been successfully developed using the numerical modeling simulator, MEDICI based on the manufacturer's processes and device information. Since lifetime is the main critical parameter for device characteristics, different analytical approaches available to date are tried to extract the *lifetime* number for the rectifier simulation model. Furthermore, besides *lifetime* number, the other physical models and model parameters are properly tuned-up for an accurate representation of the experimental data. The characterized model has been tested for various operating conditions; and a very close agreement is found between simulation and experimental data.

## ACKNOWLEDGMENTS

The authors would like to thank technicians of Applications and Characterization Laboratory of Motorola, Inc., and Application Engineers of TMA-MEDICI software for their assistance and cooperation.

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