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Scattering Parameter Approach to Power MOSFET Design for EMI

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***Abstract*— Electromagnetic interference (EMI) noise by avalanche oscillations is the major barrier to improve power device performance. Especially the oscillations of three-terminal devices are more complex than two-terminal devices in point of the mutual relationship between devices and external circuit. Scattering parameter (S-parameter) under avalanche condition is obtained to establish stable-unstable criterion with stability factor (K-factor). The stable-unstable criterion clearly indicates the unstable frequency range with each change in MOSFET design. In addition the oscillation mechanism on power MOSFET is modeled with junction capacitance, which is the same as that of diode. For EMI suppression, resonant frequency of external circuit has to be different from unstable frequency of MOSFETs.**

Keywords-scattering parameter; stability factor(K-factor): power MOSFET; EMI; two-ports; dynamic avalanche; three-terminal; negative resistance

I. INTRODUCTION

EMI noise is the major barrier for improving power device performance. EMI noise is often observed during avalanche period [1], shown in Fig. 1 as an example, when thin drift layer is employed to reduce the on-resistance of the MOSFET. In further improvement of the power MOSFET, it is required to prevent EMI from the view point of the close mutual relation between device and circuit including stray inductance/capacitance. Unlike diode oscillations, three-terminal device oscillations significantly increase their complexity, specially, due to the external circuit configuration influence.

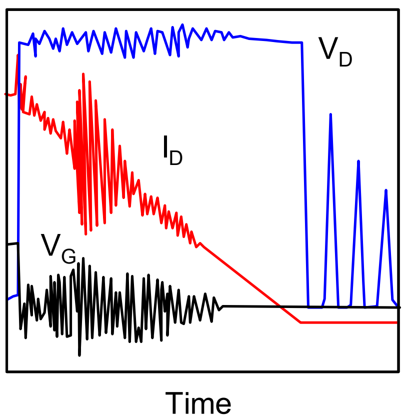


Figure 1. Schematic waveform of oscillation during avalanche period.

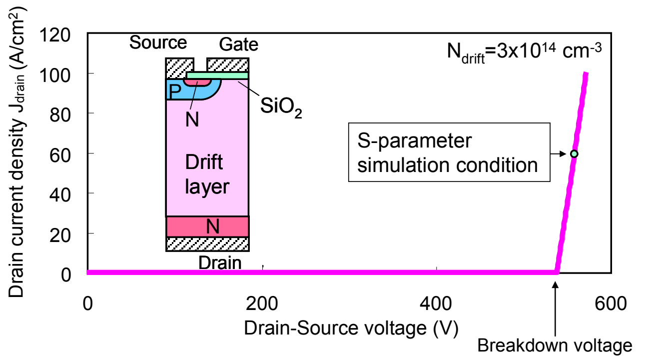


Figure 2. Blocking characteristic and S-parameter simulation condition with TCAD.

Most of reported investigations have discussed the oscillations on two-terminal devices and three-terminal devices [1-13]. Some of instability investigations on power MOSFETs have analyzed the mechanism from the view point of inside capacitances of MOS gate or PN junction by numerical simulation [1-4]. Furthermore current filament and lifetime control add the complexity of the oscillations under avalanche condition [5-9]. And some investigations mentioned the suppressing method of the instability, such as one-port AC analysis [10, 11] or special diode structure [12].

This paper proposes adoption of two-port S-parameter approach to three-terminal power device oscillation model, for the first time, to cover entire condition for avalanche induced oscillations. The purpose of this work is to establish a systematic approach to suppress the noise with clear stability criterion for three-terminal devices.

II. Two-Ports Scattering Parameter Approach

S-parameter matrix (S_{ij}) under avalanche condition is obtained as shown in Fig. 2 to analyze the AC power reflection and transmission in the MOSFET by frequency domain TCAD simulation. S_{22} clearly shows the existence of instability under avalanche condition in the frequency range around 1 GHz as shown in Fig. 3. The S_{22} also indicates the increase of the instability on power MOSFET with the lowering of doping concentration in N-drift layer (N_{drift}). Different from S_{22}, S_{11} is identical and stable regardless of doping concentration. S_{12} and S_{21} are negligibly small value which is less than ten to the minus second power.

From the S-parameter matrix, it is considering AC power reflection is dominant especially at output side.

III. Systematic Noise Suppression Approach with Stability Factor (K-factor)

The K-factor is calculated from S-parameter matrix (See appendix) to predict as stable-unstable frequency. MOSFETs with lowery doped N-drift layer have wider unstable frequency range over 1 GHz as shown in Fig. 4, which is the same as that of trend as S_{22}. MOSFETs with highly doped N-drift layer

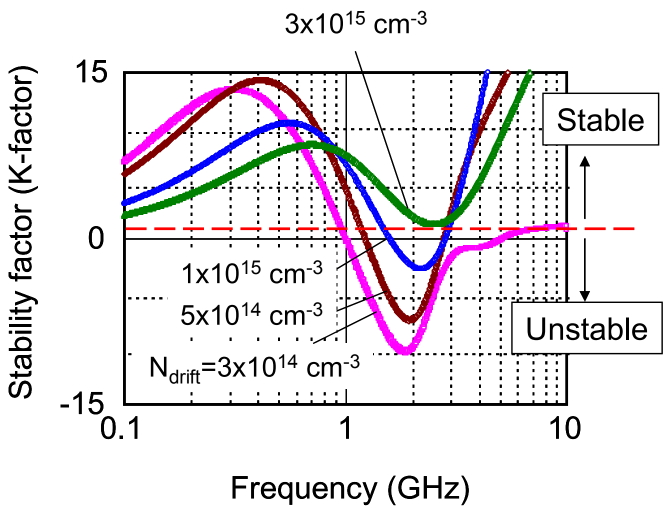


Figure 4. Stability factor (K-factor) calculated from S-parameters.

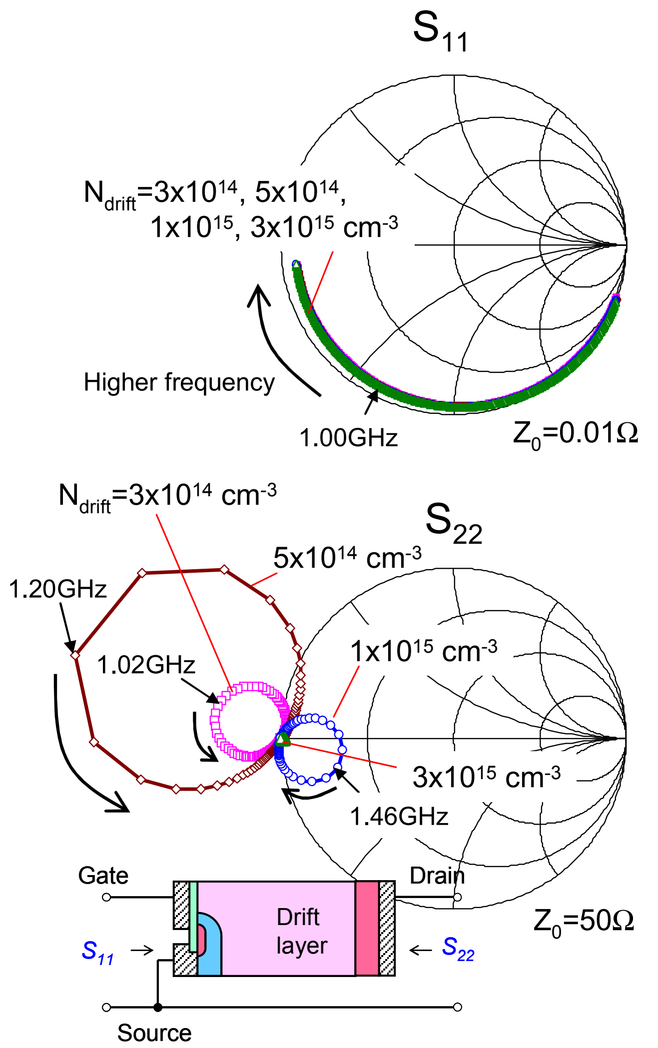
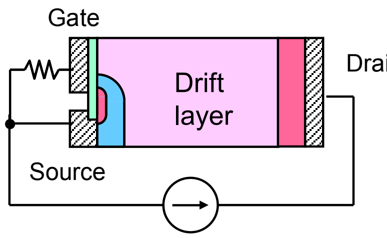
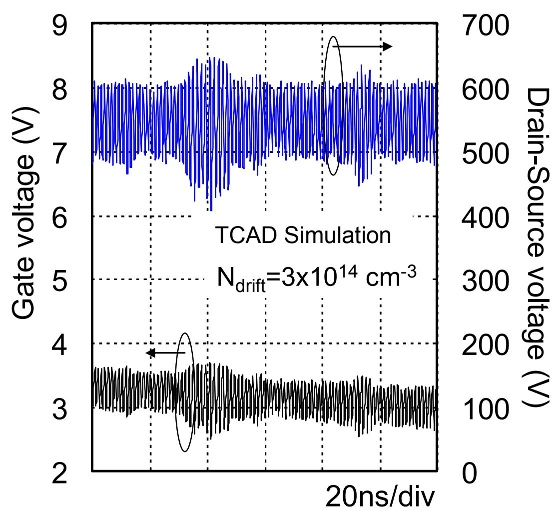


Figure 3. S-parameters with different doping concentration of drift layer. The analyzed frequency range is 0.1 GHz to 10 GHz.



(a) Constant current method



(b) Reproduced drain oscillation and gate oscillation

Figure 5. Reproduced oscillations during avalanche mode obtained by TCAD.

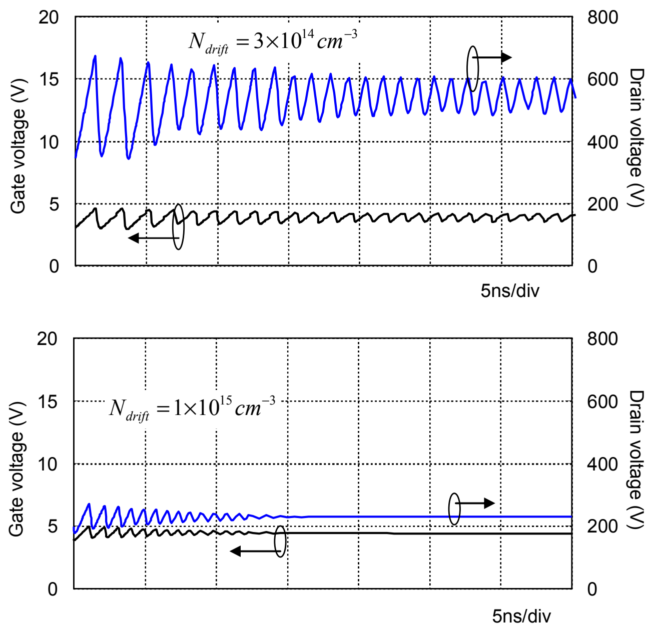


Figure 6. Continues oscillations and damped oscillation corresponding with Stability factor and S-parameter.

improve the stability while on-resistance and blocking voltage got lower.

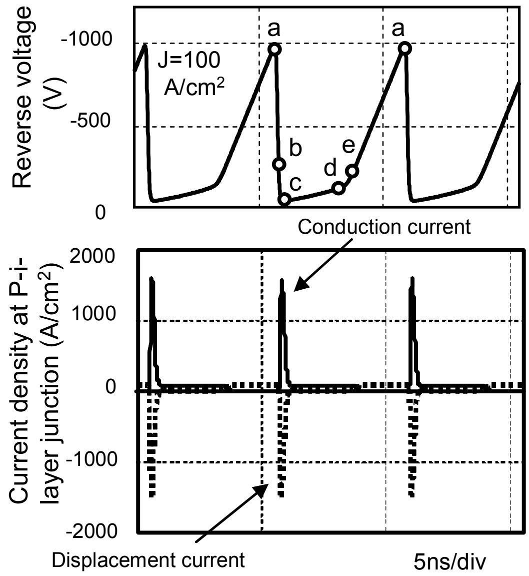
TCAD time domain simulation with constant current source reproduces the high frequency avalanche oscillations [4], under a certain current density as shown in Fig. 5. The constant current method has advantages of short simulation time and simple procedure because the current represents avalanche current. The avalanche oscillations vary with various doping concentration in drift layer as shown in Fig. 6. The drain voltage oscillations of low doping N-layer concentration for example 3×10^{14} cm^{-3} continue with gate voltage oscillation having same oscillation frequency. The oscillations of high doping N-layer concentration of 1×10^{15} cm^{-3} don't continue with damping and are completely disappeared after 15 ns. It is considering that gate waveform is affected by the drain oscillation because S_{11} is stable and the both oscillations have same frequency.

Oscillation criterion with stability factor substantially corresponds with the stable-unstable frequency. For EMI suppression, external circuit has to be designed with self resonant frequency outside the unstable frequency range indicated by the criterion.

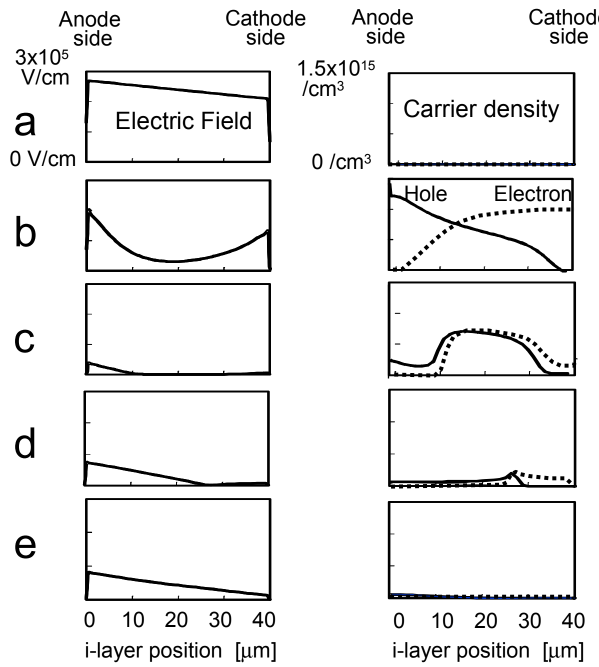
IV. Mechanism Comparison between Power MOSFET and PiN Diode

Typical drain voltage oscillations by avalanche phenomenon have special shapes of saw-tooth or triangle, which vary with drift layer design and current density. The shapes are also observed on PiN diode during reverse recovery and reproduced with the constant current method as shown in Fig. 7.

The mechanism of saw-tooth shape on the diode is described in the next. Just after reaching the highest voltage in the waveform at point "a", avalanche phenomena occurs so as to discharge the junction capacitance with lowering of electric



(a) Waveforms of voltage, conduction current and displacement current.



(b) Electric field and carrier density distribution in i-layer

Figure 7. Simulated waveforms and behavior of electric field and

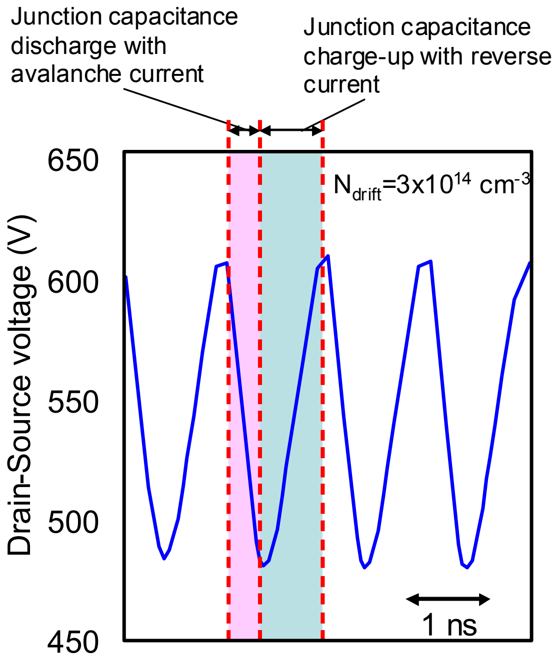


Figure 8. Oscillation obtained by TCAD simulation and the mechanism with junction capacitance model.

field intensity (point "b") and the generated carriers are stored in the lightly doped layer (i-layer) at point "c". The displacement current density at the PN junction is as high as 1600 A/cm^2 during the sudden drop of the voltage and the corresponding conduction current flows due to the avalanche injection into drift layer. The stored carriers are gradually swept out with expanding of weak electric field area (point "d") after the sudden drop of the voltage. After the stored carriers are entirely swept away from the drift layer (point "e"), the junction capacitance is charged again by the reverse current until the highest voltage (point "a"). The triangle oscillation only has the two periods of discharge and charge of junction capacitance without low dv/dt period from "c" to "d" thanks to lower carrier generation.

The oscillation mechanism on the PiN diode is an alternate charge-discharge cycle of the junction capacitance and it is thought to be common for all kinds of power devices because junction capacitance exists between output terminals of all the devices. The discharge from junction capacitance of MOSFET as shown in Fig. 8 causes power reflection between output terminals expressed by S_{22} and induces EMI noise.

V. Conclusion

The stable-unstable criterion by stability factor with scattering parameter is proposed to suppress the EMI noise of three-terminal power devices. The criterion is systematically obtained with AC parameters by TCAD frequency domain simulation and clearly indicates stability and oscillation frequency on power MOSFET. The criterion is well expressed with unstable frequency induced by avalanche phenomenon. The oscillation mechanism is discharge and charge-up of junction capacitance and it is common for all kinds of power devices structurally. To suppress EMI, external circuit has to be designed with unmatched resonant frequency for the unstable frequency of the power devices.

Appendix

K-factor is calculated by the following equation with S-parameter matrix. It indicates stable-unstable criterion as functions of frequency.

$$K = \frac{1-|S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{12}S_{21}|^2}{2|S_{12}S_{21}|}$$

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