A Fast Doping Profile Optimization Method for Power Devices

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INTRODUCTION

In power devices such as power MOSFETs and insulated-gate bipolar transistors (IGBTs), the on-resistance and breakdown voltage are important device characteristics. In order to improve these characteristics, device structures with specific doping profiles have been proposed [1] [2]. These doping profiles lead to improvements of the on-resistance and breakdown voltage due to carrier accumulation and electric field reduction, respectively. Such doping profile design can be formulated as the optimization problem of doping profile. Several studies have been carried out on mathematical optimization of doping profile for submicron devices [3] [4], and a fast optimization approach using the adjoint method was reported [5]. However, no mathematical optimization for power devices has been reported because of the large-scale analysis required. In this paper, a fast doping profile optimization method for power devices is proposed.

METHODOLOGY

It is known that for power devices, there is a tradeoff between the on-resistance and the breakdown voltage [6]. In order to optimize this tradeoff, the present study attempts to decrease the peak value of the electric field while limiting the increase in the on-resistance. This is formulated as the following minimization problem, whose objective function is the peak electric field and whose constraint is the on-resistance:

$$\underset{C}{\text{minimize}} \ \max|E|, \text{ subject to } R_{\text{on}}^{\text{opt}} \leq R_{\text{on}}^{\text{init}}, \quad (1)$$

where C is the doping concentration, E is the electric field, and $R_{\text{on}}^{\text{opt}}$ and $R_{\text{on}}^{\text{init}}$ are the on-resistances of the optimal and initial structures, respectively.

A flow chart for the optimization method is shown in Fig. 1. The drift diffusion model is used as the fundamental equation for power devices, the adjoint method is used as a sensitivity analysis method to reduce the execution time, and the sequential quadratic programming method [7] is used to update the doping profile.

RESULTS

Fig. 2 shows the initial and optimal doping profiles for a p-n diode. It can be seen that in the optimal profile, an intrinsic layer appears near the p-n junction. As seen in the current-voltage curves Fig. 3, although the on-resistance is the same for both structures, the breakdown voltage is increased using the optimized profile. Thus, a better tradeoff between the on-resistance and breakdown voltage is obtained.

Fig. 4 shows the initial and optimal doping profiles for an edge termination. It can be clearly seen that for the optimal doping profile, the p-type region is expanded. Furthermore, the electric field distributions shown in Fig. 5 indicate that the high electric field concentration is eliminated as a result of the optimization process, corresponding to an improvement in the breakdown characteristics. The above results indicate that the proposed method is useful for developing novel device structures.

Table I shows the execution time for the adjoint method used in the present study and a conventional finite difference sensitivity analysis. It can be seen that the adjoint method can drastically reduce the execution time and enable fast optimization.

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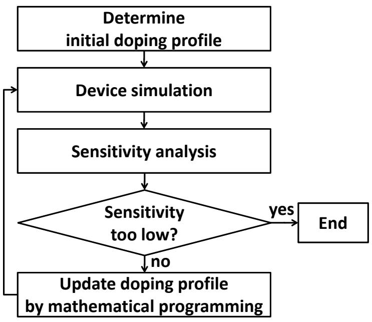
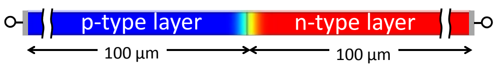
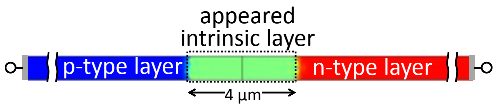


Fig. 1. Flow chart of doping profile optimization procedure. After the initial doping profile is determined, a device simulation is carried out. This is followed by a sensitivity analysis. If the sensitivity is too low, the calculation is stopped. If not, the doping profile is updated by mathematical programming to improve the objective function while satisfying the constraint. The optimal profile is determined by repeating the device simulation, sensitivity analysis and profile update steps.

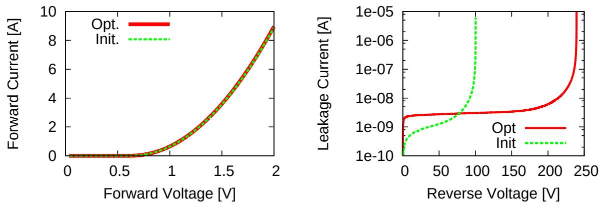


(a) Initial doping profile



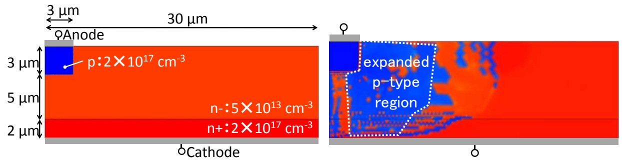
(b) Optimal doping profile

Fig. 2. (a) Initial and (b) optimal doping profiles for a diode. Optimization leads to the appearance of an intrinsic layer near the p-n junction.



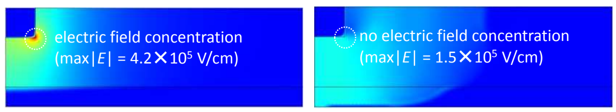
(a) Forward bias (b) Reverse bias

Fig. 3. Current-voltage curves for initial and optimal diode structures under (a) forward bias, where the curves are identical because of the on-resistance constraint, and (b) reverse bias, where the breakdown voltage is increased from 100 V to 240 V by optimization.



(a) Initial doping profile (b) Optimal doping profile

Fig. 4. (a) Initial and (b) optimal doping profile for edge termination. The p-type region is expanded following optimization.



(a) Initial profile (b) Optimal profile

Fig. 5. Electric field distribution around an edge termination for (a) the initial structure, in which a high electric field concentration is present, and (b) the optimal structure, in which this concentration is eliminated. The peak value of the electric field is reduced from 4.2×10^5 V/cm to 1.5×10^5 V/cm, leading to an improvement in the breakdown characteristics.

TABLE I
EXECUTION TIME PER UPDATE.

Type	No. of Elements	Sensitivity analysis method	Exec. time per update [s]
1-D	108	adjoint	0.21
		finite difference	32
2-D	3140	adjoint	2.4
		finite difference	6788