A Rapid Convergence Device-Circuit Complete Coupled Simulation

Ichiro Omura, Akio Nakagawa
Research & Development Center, Toshiba Corp.
1 Komukai Toshibacho, Saiwai-ku, Kawasaki, 210 Japan
Phone 044-549-2095, Fax. 044-555-2074

1. Introduction

Device-circuit complete coupled methods, which simultaneously solve the device and circuit equations, efficiently reduce the number of Newton iteration.

However, much CPU time is requierd for a single Newton iteration, if conventional coupled solution algorithm is adopted, because circuit-device interaction breaks the block-five-diagonal form of Jacobi matrix obtained from a finite difference discretization scheme.

This paper proposes a new efficient algorithm for device-circuit complete coupled solution method which keeps the diagonal form of Jacobi matrix even for an arbitrary external circuit, for the first time. Thus, the method can greatly reduce CPU time required for a single Newton iteration as compared with conventional coupled method.

2. A new external circuit solution technique

Each circuit component is assigned between two adjacent grid points which are generated outside the calculated device area and merges the originally generated grids inside the device, as shown in Fig.1. One problem is that the external circuits contact one of the device electrodes in a point. This is successfully overcome by treating the electrodes as those having finite resistance, and the equation $J=\sigma E$ is solved inside the electrode. In actual devices, external circuits contact the electrode through a bonding pad. Thus, this treatment is naturally justified.

2-1 Efficient circuit construction techniques

The proposed method assigns each circuit component between two adjacent grid points. External circuits, however, sometimes require to connect distant points with the same voltage. This problem can be solved by connecting the two points through a series combination of imaginary components. For example, consider a gird point A is connected to a distant point B as shown in Fig.2(a). The equivalent replacement for this is a series connection of two resistors of 1 ohm and a imaginary resistor having negative resistance of -2 ohm as shown in Fig2.(b). It was found that this yields the desired results without causing numerical instability.

A method to simplify the generated Jacobi matrix is further found if there is voltage or current sources in the external circuits. Terms for voltage or current sources can be excluded from the Jacobi matrix because they can be considered as boundary value problems. If there is a voltage source, the circuit can be disconnected by eliminating the voltage source and applying a fixed value boundary condition, instead, to the disconnected both ends of the circuit. This method is strongly effective to reduce computation time because disconnection of circuits can eliminate coupling between two distant electrodes and, thus, keeps Jacobi matrix in five-diagonal form. Fig.3 shows such an example. A voltage source E in Fig.3(a) is replaced by the fixed value boundary condition, so that the circuit is simplified as shown in Fig.3(b), where coupling between the source and drain electrodes of the device is eliminated.

For each grid point, three independent equations associated with three variables: hole and electron densities and the potential, are assigned. Thus, these three independent equations can be used to represent circuit equations outside the device. This is useful to express complicated external circuits on the generated grid points. For example, even if paths of two circuits overlap each other as shown in Fig.4(a), these circuits can be expressed successfully using three layered grids for circuit equations as shown in Fig.4(b).

3. Detailed Circuit Model

3-1 Circuit component definition

A circuit component is defined by a function Q in the following form.

$$Q = Q(V, dV/dt, I, dI/dt) = 0 \qquad (1)$$

Where V is potential difference between both ends of the component and I is current through it, as shown in Fig.5. If the component has linear dependence on V, dV/dt, I, dI/dt, function Q can be written as,

$$Q = a\cdot V + b\cdot dV/dt + c\cdot I + d\cdot dI/dt. \qquad (2)$$

Then, the set of parameters (a,b,c,d) defines the component. For example, if the component is a resistance 'R', $Q=V+R\cdot I$. Thus, $(a,b,c,d)=(1,0,R,0)$. For a capacitance 'C', $Q=C\cdot dV/dt+I$, $(a,b,c,d)=(0,C,1,0)$. For an inductance 'L', $Q=V+L\cdot dI/dt$, $(a,b,c,d)=(1,0,0,L)$. Q=I means nothing is connected between the nodes, then $(a,b,c,d)=(0,0,1,0)$. In some cases, more than two elements can be put together into a component. For example, a series RL combination is expressed by a function $Q=V+R\cdot I+L\cdot dI/dt$, thus $(a,b,c,d)=(1,0,R,L)$.

3-2 Equation for circuit node

In this section, it is assumed that each component has form (2). Substituting $(V^o-V)/\Delta t$ and $(I^o-I)/\Delta t$ to dV/dt and dI/dt, function(2) is rewritten as a function of V, V^o, I, I^o, as follows.

$$Q = a\cdot V + b\cdot(V-V^o)/\Delta t + c\cdot I + d\cdot(I-I^o)/\Delta t. \qquad (3)$$

Here, V^o and I^o are the potential difference and current at $t=t_o$. V and I are potential difference and current at $t=t_o+\Delta t$. Solving the equation (3)=0 for I, the current through the component is obtained as,

$$\begin{aligned} I &= I(V,V^o,I^o) \\ &= \{-[a+(b/\Delta t)]\cdot V+(b/\Delta t)\cdot V^o+(d/\Delta t)\cdot I^o\}/\{c+(d/\Delta t)\}. \end{aligned}$$

Then, the equation for each circuit node is given directly from Kirchhoff's current law ,which states that the sum of the currents entering a node is zero. Assume that four elements: Q_A, Q_B, Q_C and Q_D are assigned between a node (j,k) and the four adjacent nodes of it, while considering the current directions as in Fig.6. Then, the equation for node (j,k) can be written as follows.

$$\begin{aligned} 0 &= I_A-I_B+I_C-I_D \\ &= I_A(\phi(j,k)-\phi(j-1,k), \phi^o(j,k)-\phi^o(j-1,k), I^o_A) \\ &\quad - I_B(\phi(j+1,k)-\phi(j,k), \phi^o(j+1,k)-\phi^o(j,k), I^o_B) \\ &\quad + I_C(\phi(j,k)-\phi(j,k-1), \phi^o(j,k)-\phi^o(j,k-1), I^o_C) \\ &\quad - I_D(\phi(j,k+1)-\phi(j,k), \phi^o(j,k+1)-\phi^o(j,k), I^o_D). \end{aligned}$$

Here ϕ and ϕ^o are node potentials at $t=t_o+\Delta t$ and at $t=t_o$. I^o_A I^o_D are currents at $t=t_o$.

3-3 Equation for device-circuit interface

The device and the circuit are connected at one point on a resistive electrode. Assume that the circuit contacts with the device at a mesh point (l,m) on a resistive electrode as in Fig.7. Then the current continuity equation for the mesh point (l,m) is written as,

$$I_{cir} = \int_{\delta\Omega} J\cdot n\, dS = 0 \quad \text{for } \Omega .$$

Here, Ω and $\delta\Omega$ are the control volume and its surface corresponding with the mesh point (l,m), where J and n are the current in the resistive electrode and normal vector to the surface $\delta\Omega$.

4. IGBT turn-off analysis with considering gate circuit influence

IGBT turn-off waveform can be accurately simulated by taking an exact external gate circuit into account. In a conventional numerical simulations of IGBT turn-off, gate voltage Vg was assumed to have a constant gradient, dVg/dt for simplicity.

Fig.8 shows a cross-section of an IGBT and the circuit used for the analysis. The numerical simulation had been carried out using the TONADDEII C program which is implemented the proposed device-circuit coupled method. The required Newton iteration number was only 3 to 4 for each time step.

The exact turn-off waveform considering the gate circuit influence has been obtained, for the first time (Fig.9). The results agreed very well with experiments.

References

[1] A.Nakagawa et al.,Proc. of NASECODE-V ,p.295(1987).
[2] A.Nakagawa et al.,Proc. of 1990 ISPSD,p32(1990).

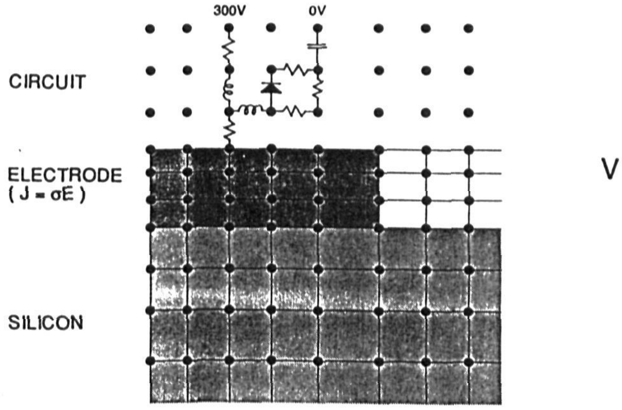


Fig.1 Schematic illustration of the method. Each circuit component is assigned between adjacent grid points outside the device.

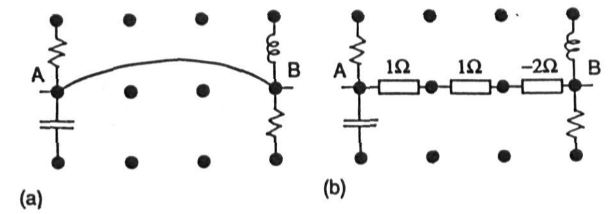


Fig.2 (a)Grid point A is connected to a distant point B. (b)Equivalent replacement for (a) is a series connection of two resistors of 1 ohm and an imaginary resistor with negative resistance of -2 ohm.

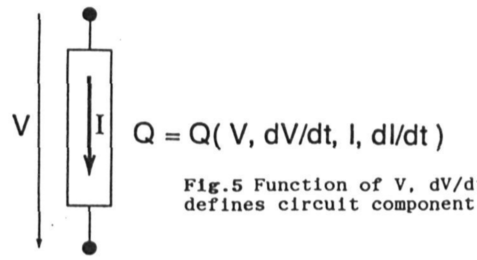


Fig.5 Function of V, dV/dt, I, dI/dt defines circuit component.

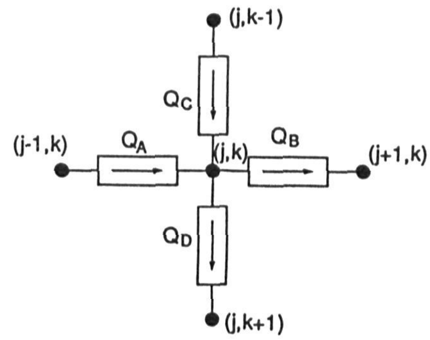


Fig.6 Four elements Q_A, Q_B, Q_C, Q_D are merged into grid point (j,k). Equation of the point is $0 = I_A - I_B + I_C - I_D$.

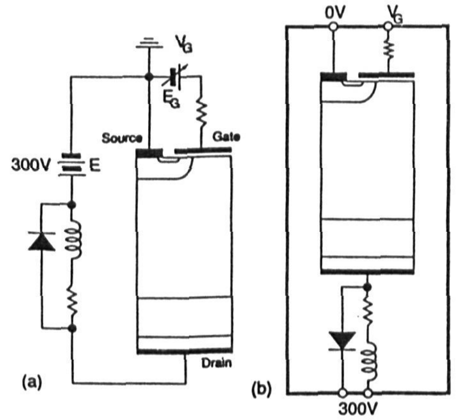


Fig.3 Voltage source in (a) is replaced by a fixed value boundary condition, so that the circuit is simplified(b).

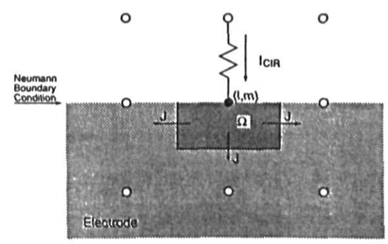
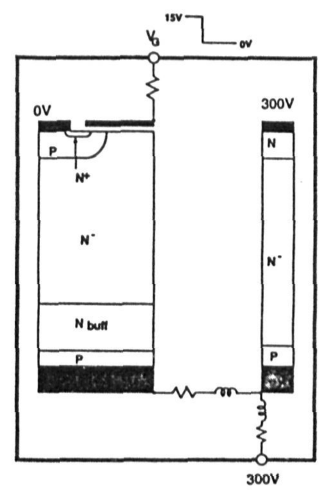


Fig.7 Device and circuit are connected at a grid point (l,m) on a resistive electrode.

Fig.8 Cross-section of IGBT and diode. Internal Neumann condition completely excludes electrical interaction between the two devices. The circuit used in this simulation is shown in the figure as well. IGBT, diode the entire circuit are completely coupled.



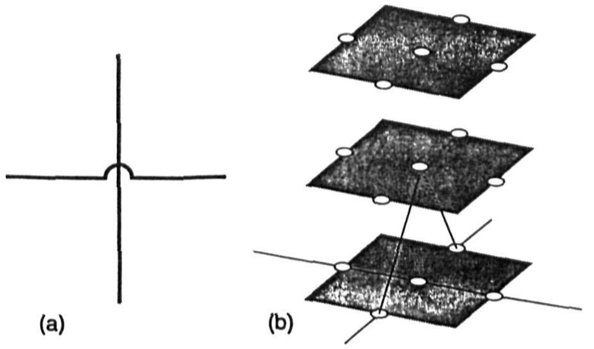


Fig.4 (a)Paths of Circuits overlap each other. (b)Circuits can be expressed using three layered grids.

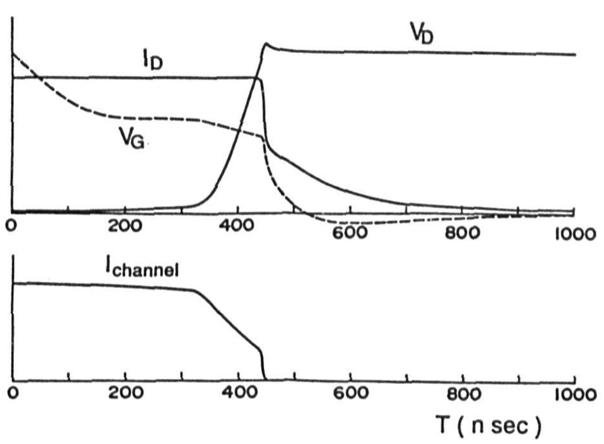


Fig.9 Obtained turn-off waveform with considering gate circuit influence.