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A model for the resonant tunneling semiconductor-controlled rectifier

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Abstract

A new switch called a resonant-tunneling-semiconductor-controlled rectifier (RT-SCR) has been proposed. A two-transistor model is used for the device. One of the transistors in the two-transistor model is assumed to be a resonant tunneling transistor (RTT), while the other transistor is taken to be a bipolar transistor. The current–voltage relationships of the device have been numerically obtained and compared with the traditional thyristor characteristics. The new device requires smaller turn-on gate voltage than a comparable traditional device for the same gate current. This indicates that in comparison with the traditional thyristor, a smaller control current may be used to turn on the device at a particular voltage.

Keywords: Semiconductor devices; Resonant tunneling devices; SCRs

1. Introduction

The pnpn thyristor structure has been around and used as a semiconductor switch to handle large amounts of currents. As the current handling capacity of the thyristor increases, the turn-on current levels, too, increase. Sometimes, another thyristor may be required to supply the turn-on current. Of course, this complicates the control circuitry. This has led to the invention of devices such as the IGBT.

Traditionally, the pnpn thyristor structure is modeled with two transistors: a pnp transistor and an npn transistor—the base of each transistor is connected to the collector of the other transistor. The turn-on gate current of the thyristor is the base current of the npn transistor in the model. With an anticipation of reducing the turn-on current, we have replaced the npn transistor with a resonant tunneling transistor (RTT) and obtained the numerical current–voltage relationships of the structure. A pnpnpn AlGaAs/GaAs heterostructure has been used in the simulation. It is suggested that the resulting device be called a resonant-tunneling-semiconductor-controlled rectifier (RT-SCR).

In this work, the tunneling characteristics of a resonant tunneling bipolar transistor (RTBT) are outlined, and a model for the RT-SCR is given. The simulation results are presented.

2. Resonant tunneling transistor current–voltage relationship

The RTBT was conceived in 1985 by Capasso and Kiehl. It was a good candidate for high-frequency oscillator and high-speed switching applications. The voltage–current relationship of an RTT is similar to a resonant tunneling diode (RTD) current expression:

$$J = \left(\frac{2e}{8\pi^3\hbar}\right)\int(\nabla_{kl}E)\,T_u^{*}T_u[f(E)-f(E+|\mathrm{e}|V)]\,\mathrm{d}^3k, \qquad (1)$$

where kl is the wave vector component perpendicular to the junction interface; E the electron energy; T_u the transmission probability; V the applied voltage; d^3k the the volume element in the wave vector; $f(E)$ the Fermi electron distribution function [1]. The current–voltage characteristic of the RTD may be obtained by placing an RTD in series with the emitter of a heterojunction bipolar transistor

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(HBT) [2], which results in the following voltage and current expressions:

$$I_{\mathrm{E_{RTT}}} = I_{\mathrm{RTD}} = I_{\mathrm{E_{HBT}}}, \tag{2}$$

$$V_{\mathrm{BE_{RTT}}} = V_{\mathrm{RTD}} + V_{\mathrm{BE_{HBT}}}, \tag{3}$$

$$I_{\mathrm{C_{RTT}}} = I_{\mathrm{C_{HBT}}}, \tag{4}$$

$$I_{\mathrm{B_{RTT}}} = I_{\mathrm{B_{HBT}}}, \tag{5}$$

$$V_{\mathrm{BE_{HBT}}} = V_T \ln\left[\frac{[\alpha_{\mathrm{F}} I_{\mathrm{E_{RTD}}}/I_{\mathrm{S_{HBT}}} + \alpha_{\mathrm{F}} + 1]}{[1 - \alpha_{\mathrm{F}}\,\mathrm{e}^{-V_{\mathrm{CE_{HBT}}}/V_T}]}\right], \tag{6}$$

$$V_{\mathrm{BC_{HBT}}} = V_{\mathrm{BE_{HBT}}} - V_{\mathrm{CE_{HBT}}}. \tag{7}$$

Collector and base currents can be calculated using the voltage value, $V_{\mathrm{BE_{HBT}}}$ as follows:

$$I_{\mathrm{C_{HBT}}} = I_{\mathrm{S_{HBT}}}\left[\left(\mathrm{e}^{V_{\mathrm{BE_{HBT}}}/V_T} - 1\right) - \frac{(\mathrm{e}^{V_{\mathrm{BC_{HBT}}}/V_T} - 1)}{\alpha_{\mathrm{R}}}\right], \tag{8}$$

$$I_{\mathrm{B_{HBT}}} = I_{\mathrm{E_{RTD}}} - I_{\mathrm{C_{HBT}}}. \tag{9}$$

Here, α_{F} and α_{R} are forward and reverse common-base current gains while $I_{\mathrm{S_{HBT}}}$is the scale current of the HBT for the given bias conditions.

3. Resonant-tunneling-semiconductor-controlled rectifier

The circuit given in Fig. 1 is used to model the RT-SCR structure. It is the modified two-transistor model, which has T_1 as a traditional bipolar transistor and T_2 as an RTT [8].

3.1. The current equations

The emitter current of T_2 is the resonant tunneling current$I_{\mathrm{E1}} = I_{\mathrm{ERTT}}$. For the devices in Fig. 1, the following equalities hold.

$$I_{\mathrm{CRTT}} = I_{\mathrm{C2}}, \tag{10}$$

$$I_{\mathrm{BRTT}} = I_{\mathrm{B2}}, \tag{11}$$

$$I_{\mathrm{ERTT}} = I_{\mathrm{RTD}}. \tag{12}$$

Because of the connection of the two transistors,

$$I_{\mathrm{B1}} = I_{\mathrm{CRTT}}, \tag{13}$$

$$I_{\mathrm{C1}} = I_{\mathrm{BRTT}} + I_{\mathrm{g}}. \tag{14}$$

The base current for the pnp transistor and the collector current of the npn transistors are as follows:

$$I_{\mathrm{B1}} = (1 - \alpha_1) I_{\mathrm{ART}} - I_{\mathrm{CO1}}, \tag{15}$$

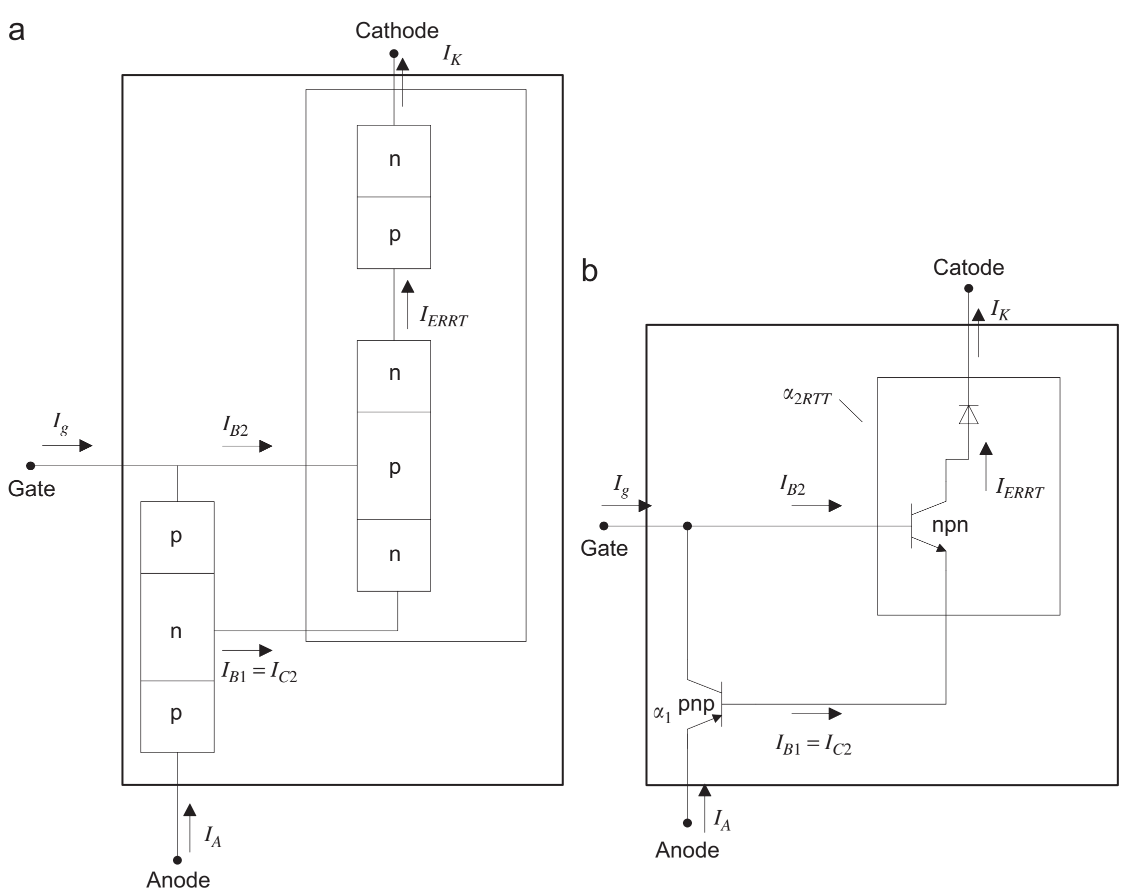

Fig. 1. Currents in a two-transistor model for the RT-SCR: (a) the semiconductor regions, (b) circuit symbols.