CHIN. PHYS. LETT. Vol. 37, No. 4 (2020) 044203

Influence of Hot-Carriers on the On-State Resistance in Si and GaAs Photoconductive Semiconductor Switches Working at Long Pulse Width *

Chong-Biao Luan(栾崇彪), Hong-Tao Li(李洪涛)**

Key Laboratory of Pulsed Power, Institute of Fluid Physics, China Academy of Engineering Physics, P. O. Box 919-108, Mianyang 621900

(Received 16 November 2019)

We demonstrate that the transport of hot carriers may result in the phenomenon where an oscillated output current appears at the waveforms in a high-power photoconductive semiconductor switch (PCSS) working at long pulse width when the laser disappears or the electric field changes. The variational laser and electric field will affect the scattering rates of hot carriers and crystal lattice in high-power PCSS, and the drift velocity of hot carriers and also the on-state resistance will be changed. The present result is important for reducing the on-state resistance and improving the output characteristics of high-power Si/GaAs PCSS.

PACS: 42.65.Re, 72.40.+w, 85.30.Fg DOI: 10.1088/0256-307X/37/4/044203

Photoconductive semiconductor switches (PCSSs) are devices in which the conductivity will increase quickly when the bulk semiconductor material absorbs appropriate light.[1,2] PCSSs have attracted a great deal of attention from researchers because of their advantages over conventional gas and mechanical switches (including high break-down field, compact geometry, fast operating time, photoelectric isolation, low jitter, high thermal conductivity, high-power density, and so on).[3–6] PCSSs are considered as the most promising devices for pulsed power applications. However, the low carrier density and ruleless transport of carriers will lead to the high on-resistance for a PCSS, which will heat the high-power PCSS, and cause thermal breakdown of the high-power PCSS.[7,8] To improve the performance of high-power PCSSs, it is necessary to study the transport characteristics of hot carriers. However, the influencing mechanism of hot carriers on the on-resistance of high power PCSSs working at long pulse width is unclear.[9,10] Thus, it is of great importance to study the transport characteristics of hot carriers under high electric field in high-power PCSSs.

In this study, an oscillated phenomenon appears on the waveform of output current in a high-power Si/GaAs PCSS working at long pulse width when the laser disappears or electric field changes. The phenomena for the Si and GaAs PCSSs are different. It is shown that the transport of hot carriers may result in this phenomenon. The present study is important for reducing the on-state resistance and improving the output characteristics of high-power Si/GaAs PCSSs.

In our experiment, the substrate materials used to manufacture the PCSS are silicon (Si) and gallium arsenic (GaAs). The resistivity of the silicon material is larger than $5 \times 10^4\,\Omega\cdot$cm, and the thickness of the Si material is 1 mm. The width and length of the rectangular Si PCSS device are 20 mm and 22 mm, respectively. The space between the two electrodes is 10 mm. The schematic diagram of prepared silicon PCSS is given in Fig. 1(a). The Al/Ni/Au alloy is deposited on the silicon surface by nano-coating technology. Two ohmic electrodes are formed by rapid thermal annealing. The measured specific resistivity is smaller than $1 \times 10^{-5}\,\Omega\cdot\text{cm}^2$. Lastly, the reflecting film is made between the two ohmic electrodes, and the antireflection film is made on the back.

The GaAs substrate material is grown by a technique known as a carbon-acceptor impurity compensated by deep EL_2 donor defects. The electric resistivity, carrier density and carrier mobility of the GaAs substrate material used to manufacture the PCSS are $1 \times 10^8\,\Omega\cdot$cm, $3.4 \times 10^{15}\,\text{cm}^{-3}$ and $5800\,\text{cm}^2/\text{V}\cdot\text{s}$, respectively. The thickness of the GaAs substrate is 1 mm.[11] The width and length of the rectangular GaAs PCSS (shown in Fig. 1(b)) are 10 mm and 20 mm, respectively. The space between the two ohmic electrodes is 10 mm. The surface damage of the GaAs substrate material is removed by a high temperature H_2 etching technology before manufacturing the ohmic electrodes. Next, the n^+-GaAs material with thickness of 100 nm and doping level of $2 \times 10^{19}\,\text{cm}^{-3}$ is grown by MOCVD on the GaAs substrate. The n^+-GaAs material between the two electrodes in the channel area is removed by ion etching. Ge/Au/Ni/Au alloy is deposited on the surface of the n^+-GaAs material. The two ohmic electrodes are formed by rapid thermal annealing. The measured specific resistivity is smaller than $10^{-6}\,\Omega\cdot\text{cm}^2$. Finally, the reflecting film is made between the two electrodes in the channel area,

*Supported by the Rector's Fund of China Academy of Engineering Physics (Grant No. YZJJLX2016002), and the National Natural Science Foundation of China (Grant Nos. 61504127 and U1530128).

**Corresponding author. Email: lihongtao-ifp@caep.cn; luanchongbiao@163.com

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and the antireflection film is made on the back.[11]

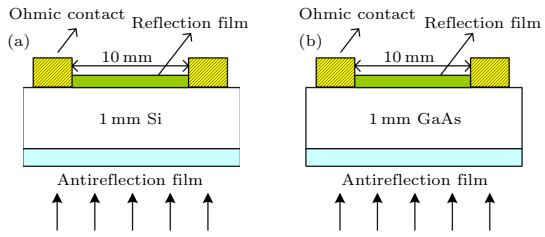

Fig. 1. Schematic diagrams of (a) Si PCSS and (b) GaAs PCSS.

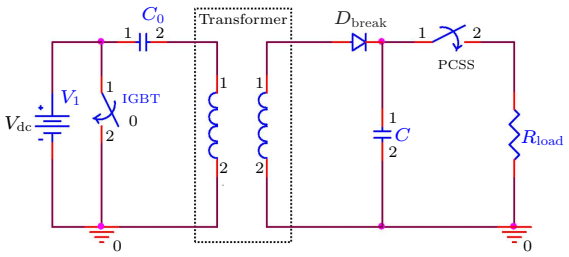

Fig. 2. Schematic diagram of the setup for testing the prepared high-power Si/GaAs PCSS.

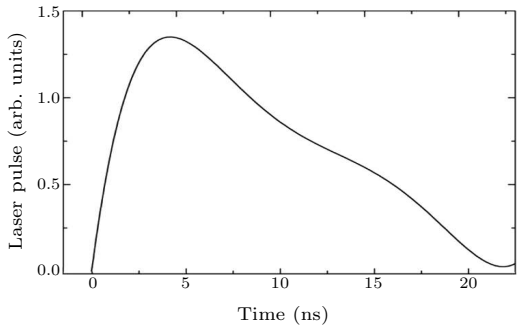

Fig. 3. Waveforms of full width at half maximum for the Q-switched frequency tripled YAG laser at 1064 nm measured by a THORLABS DET10 A/M photodiode.

The test circuit for the prepared Si and GaAs PCSSs is shown in Fig. 2. Here C_0 is the primary storage capacitor, C is a secondary charged capacitor, which provides a source current during the photo conductive pulse, and the load resistance $R_{\rm load}$ is 50 Ω. The prepared Si and GaAs PCSSs are all tested at high pulse voltage and illuminated by a Q-switched frequency tripled yttrium aluminum garnet (YAG) laser with wavelength 1064 nm, maximum optical energy 10 mJ and full width at half maximum of 15 ns (shown in Fig. 3). The photocurrents through the Si and GaAs PCSSs are measured by a Rogowsky coil with sensitivity of 1 V/A and response time of 1.2 ns. A Tektronix P6015A high-voltage probe is used to measure the input and output voltages on the Si and GaAs PCSSs. An oscilloscope with a bandwidth of 1 GHz is used to record the current and voltage waveforms.

Figures 4(a) and 4(b) show the measured output current waveforms with different laser energies for the Si and GaAs PCSSs (the capacitor C is 7 nF and the input voltage is 11 kV), respectively. It is obvious that an oscillated phenomenon appears on the waveforms of the output current when the laser disappears. For the Si PCSS, the range of oscillation increases with the increasing laser energy. However, the range of oscillation does not change with the increasing laser energy for the GaAs PCSS.

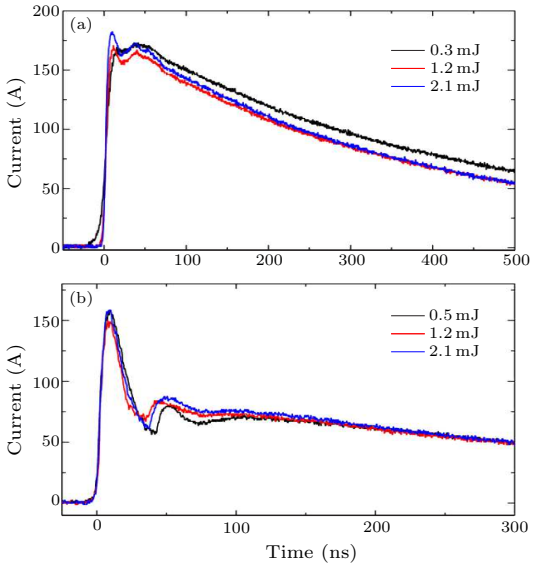

Fig. 4. Output current waveforms of the Si (a) and GaAs PCSSs (b) with different laser energies.

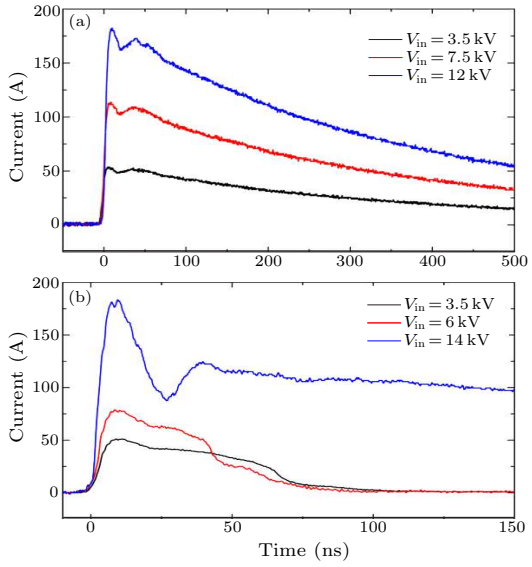

Fig. 5. Waveforms of output current for the Si (a) and GaAs PCSS (b) with different input voltage.

Figures 5(a) and 5(b) show the waveforms of the measured output current with different input voltages for the prepared Si and GaAs PCSSs (with the capacitor C is 7 nF and the laser energy is 2.1 mJ), respectively. In Fig. 5, the time range of the oscillation does not change with the increasing input voltage for the prepared Si PCSS, and the oscillation of the output current changes with the increasing input voltage for the GaAs PCSS. The reason is tentatively explained in the following.

The GaAs material is a direct bandgap semiconductor, and the GaAs PCSS can work at linear and nonlinear modes. At a nonlinear mode, the voltage across the GaAs PCSS will keep to be constant instead of dropping to 0 when the laser disappears.[12] However, the nonlinear mode of the GaAs PCSS appears only when the electric field and laser energy achieves the threshold. In our experiment, the thresholds of electric field and laser energy for our prepared GaAs PCSS are 0.8 mJ and 5 kV/cm, respectively.[12] In this work, the GaAs PCSS will work at a nonlinear mode when the laser energy is over 0.8 mJ and the loading voltage is above 5 kV. Therefore, the input voltage will affect the transport of hot carriers for the GaAs PCSS when the laser disappears, then the oscillation of output current waveforms changes with the input voltage.

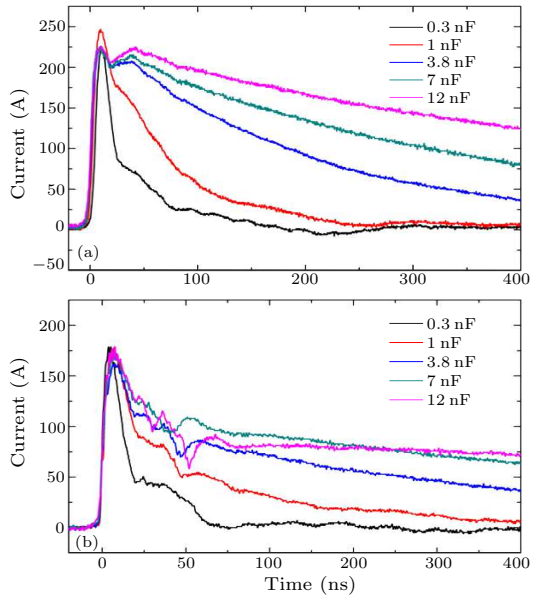

Fig. 6. Waveforms of the output current for the (a) Si and (b) GaAs PCSSs with different charge capacitor values.

Figures 6(a) and 6(b) show the waveforms of the measured output current with the charge capacitor value for the prepared Si and GaAs PCSSs (with the input voltage of 11 kV and the laser energy of 2.1 mJ), respectively. It can be seen that the oscillated phenomenon changes with the charge capacitor value for both the Si and GaAs PCSSs. When the capacitor value is large, the energy in the capacitor will be larger after 15 ns, and the electric field in the PCSS will not change compared to the initial value.

Based on the transport characteristics of hot carriers in Si and GaAs electron devices,[13–16] this oscillational phenomenon of the output current can be explained as follows: When the electric field in the Si and GaAs PCSSs is above 10 kV/cm, the transport of carriers is within high electric field, and the photo-generated carriers become the hot carriers. The scattering mechanisms that affect the hot carriers to transport are acoustics deformation potential scattering, polar optical-phonon scattering, and impurity scattering, etc. For the hot carriers, the temperature of hot carriers is higher than that of the crystal lattice, and the mobility of carriers is related with the temperature, then the effect of scattering mechanisms will be enhanced or weakened, and substantial deviations from Ohm's law occur,

$$e\mu E^2 = \left(\frac{3k_{\mathrm{B}}}{2}\right)\frac{T_{\mathrm{e}} - T}{\tau_{\varepsilon}}, \tag{1}$$

where μ is the electron mobility, E is the electric field, k_{B} is Boltzmann's constant, τ_{ε} is the energy relaxation time, T_{e} is the temperature of carrier, T is the temperature of crystal lattice. When T_{e} increases and E remains unchanged, μ will increase.

For the acoustics deformation potential scattering,[17]

$$\mu = \mu_0\left(\frac{T}{T_{\mathrm{c}}}\right)^{1/2}, \tag{2}$$

where μ_0 is the equilibrium carrier mobility, T_{c} is the temperature of hot carriers.

For the polar optical-phonon scattering and impurity scattering, the hot-carrier mobility μ is in direct proportion to T_{c}.[18,19]

When the laser energy is large, the photo-generated carriers reach saturation. The scattering rate will increase under high electric field, and the carrier mobility decreases. Then, the on-resistance increases and the output current for the prepared PCSS decrease.

When the laser disappears, the photo-generated carriers decrease. First, the scattering rate under high electric field will decrease. Second, the energy from the remaining energy (the electric field added in the PCSS) will be added to the hot carriers, and the low-angle scattering is in the ascendant. The saturation velocity of the hot carriers will increase, then the carrier mobility will also increase (based on the equation $V_{\mathrm{d}} = \mu E$, and E does not change), but the rate of the increasing mobility is related with the added electric field. Therefore, the on-state resistance decreases and the output current for the PCSS increases.[20]

When the laser energy is low (Fig. 4), the photo-generated carriers will increase all along with the laser pulse and do not reach the saturation, and the hot-carrier mobility does not change or has less change. Then, the on-state resistance decreases along with the laser pulse (the rising range is related with the laser energy), and the output currents of the prepared Si and GaAs PCSSs increase. When the laser disappears, the photo-generated carriers do not increase, and the scattering rate between the carriers decrease, so the on-resistance decrease and the output current increase. When the energy of the hot carriers obtained from the added electric field is low, and the rising rate

of hot-carrier mobility is lower than the decreasing rate of the hot carriers, the on-resistance values for the Si and GaAs PCSSs increase and the output currents decrease.

The transport of hot carriers is important for the output characteristics of high-power PCSSs. Here an oscillated phenomenon appears on the waveforms of output currents in high-power Si and GaAs PCSSs working at long pulse width when the laser disappears or electric field changes. The experimental results show that the phenomena for the Si and GaAs PCSS are different. The transport of hot carriers under high electric field may result in this oscillated phenomenon. Analysis of the oscillated phenomenon will be helpful for reducing the on-resistance and improving the output characteristics of high-power PCSSs.

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