Photo-sensitive characteristics of negative resistance turn-around occurring in SIPTH*

Ji Tao(季涛)[1,†], Yang Licheng(杨利成)[2], Li Hairong(李海蓉)[2], He Shanhu(何山虎)[2], and Li Siyuan(李思渊)[2]

(1 School of Fundamental Studies, Shanghai University of Engineering Science, Shanghai 201620, China)

(2 Institute of Microelectronics, School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China)

Abstract: Influences of light irradiation on the negative resistance turn-around characteristics of static induction photosensitive thyristor (SIPTH) have been experimentally and theoretically studied. As the gate current of SIPTH is increased by the light irradiation, the potential barrier in the channel is reduced due to the increase in voltage drop across the gate series resistance. Therefore, SIPTH can be quickly switched from the blocking state to the conducting state by relatively low anode voltage. The optimal matching relation for controlling anode conducting voltage of SIPTH by light irradiation has also been represented.

Key words: static induction photosensitive thyristors; gate series resistance; double injection effect; potential barrier; light-generated carriers

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1. Introduction

Static induction thyristors (SITH) are widely used in switching applications[1−7]. SITH frequently switch between the conducting-state and blocking-state. The switching process of SITH is the transition process from conducting-state to blocking-state, or vice versa. The switching speed and the sensitivity of conducting are the dynamical parameters to describe switching performances of SITH. The experimental results demonstrated that a number of additional electron–hole pairs were generated in the channel of SITH under the light irradiation, giving rise to abnormal *I*–*V* characteristics. It not only changed the current of each electrode, but also reduced the anode voltage required for the negative resistance turn-around in *I*–*V* characteristics to occur. In order to use this photoelectric effect to further improve the switching performances and conducting sensitivity of SITH, static induction photosensitive thyristors (SIPTH) were designed and fabricated, and the effects of light irradiation on the mechanism of negative resistance and turn-around anode voltage were theoretically researched and simulated in this paper.

SIPTH is a new kind of solid state photosensitive devices. In structure an SIPTH is equivalent to the many photosensitive diodes in parallel and static induction transistor with excellent linearity, high gain, wide frequency band and low noise. It consists of pin photosensitive diodes surrounding the p^+ gate region and SITH. The gate potential of SIPTH is modulated by the light-generated excess carriers, therefore the anode current is controlled through the regulation of the potential barrier in channel. As a static induction transistor (SIT) with high current gain, excellent linearity, low noise and wide frequency band is comprised in SIPTH, it can amplify the light signal, making it superior in control sensitivity to any other photosensitive devices. It can be widely used in micro-light measurement, photon counting and detection of ray or particles.

As the transmission time of carriers and the junction capacitance is much decreased due to pin diodes included in SIPTH, the frequency characteristics and the response speed are greatly improved. Therefore, SIPTH is a very promising photosensitive device, and will be widely used in many switching application regions.

At present, there are mainly two different viewpoints on the negative resistance characteristics of SITH: double injection effect[1] and de-bias effect[2]. The experiment and simulation indicated that the negative resistance turn-around characteristics were resulted from their cooperation effect.

2. Device structure and fabrication

In order to research the switching characteristics of SIPTH in the presence of light irradiation, an SIPTH has been fabricated with surface gate structure using n-type crystal Si substrate of 80–100 Ω·cm resistivity. Due to high electron mobility of n-type Si, the saturation drift velocity of electron is larger than that of hole, thus the transit time of carriers in channel of SITH is much shorter, giving a excellent frequency characteristics. The cathode, gate, channel and anode regions were doped at impurity concentrations of $N_K = 1\times10^{19}$ cm^{-3}, $P_G = 1\times10^{19}$ cm^{-3}, $N_{CH} = 4\times10^{13}$ cm^{-3} and $P_A = 1\times10^{19}$ cm^{-3}, respectively. The region between two gates is called channel region whose length is 7 μm. The n^- region outside the channel between the gate and anode is referred to as drift region. The gate-to-gate space is 15 μm, the width of gate stripe is 10 μm, and the repetition period is 25 μm. The cathode and

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† Corresponding author. Email: jit626@sues.edu.cn

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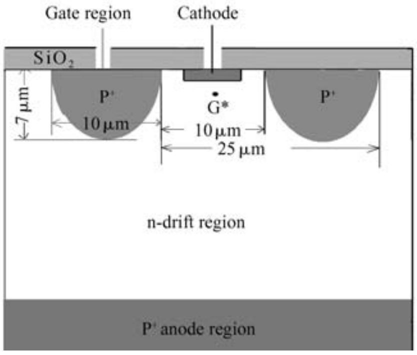

Fig. 1. Cross-section of a segment of SIPTH with surface gate.

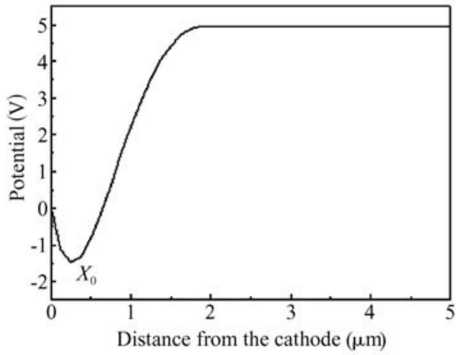

Fig. 2. Potential distribution along the channel in the blocking-state.

gate stripes were alternatively arranged at the surface to make it easy to connect many units in parallel as shown in Fig. 1.

A single crystal p-Si heavily doped at boron concentration of 1×10^{19} cm^{-3} was used as the original wafer, also as the p$^+$ anode region of SIPTH. An n-type epitaxial layer with light doping of phosphorus concentration of 4×10^{13} cm^{-3} is grown on wafer surface to the thickness of 40–45 μm as the channel and drift region of SIPTH. The gate stripes were formed by selective high-density boron diffusion at the surface of epitaxial layer, of which the diffused depth is about 7 μm. The cathode regions between two gate stripes at the surface of epitaxial layer are formed by the high-density boron diffusion, the diffused depth is about 1 μm. In order to enhance the absorption of light, a SiO_2 film is deposited on the surface to increase the penetration ratio. The light is incident upon the top surface on which the gates and cathodes are alternatively arranged. The description of other conventional processes was omitted to reduce the length of this paper.

3. Measurement and operation features

In order to measure the electrical performances of SIPTH under light irradiation, the device was biased as follows: the cathode was biased to zero voltage as the reference potential, the anode was positively biased with high voltage V_{AK}, and the cathode was reversely biased with negative voltage V_{GK}.

As the gate potential is the lowest in device's bias configuration, the pin diode composed of the cathode and gate was reversely biased. The depletion layers built by reversely or zero biased p$^+$n$^-$ junctions pinch off the channel from the cathode to the anode. A saddle point of potential barrier is established in the channel. The carrier injection is controlled by the potential barrier in the channel, whose height is determined by the gate and anode voltages. Before the negative resistance turn-around occurs, the potential barrier in channel is so high that the holes injected from the anode can hardly arrive at the cathode by drift motion through the drift region. Only a very small portion of the electrons injected from the cathode can reach the anode. Although the pin diode between the anode and cathode is forwardly biased on this condition, there is almost no anode flowing in the channel. The gate current consists of the reverse saturation current of gate-cathode junction and the current of long base p$^+$n$^-$p$^+$ structure between the gate and the anode, which is very small and can be ignored if the negative gate voltage is not very high and before the negative resistance turn-around occurs.

The electron–hole pairs are generated in the depletion region by light irradiation incident on the surface of device. The light-generated electrons drift towards the anode, whereas the light-generated holes move to the p$^+$ gate. The most of the light-generated holes drift to the gate region and accumulate there, because the potential of gate region is the lowest in the device. The steady accumulation of holes results in an increase in gate potential and a decrease in depletion layer width of gate-channel junction. The reduction in the height of potential barrier in the channel resulting from the increase in gate potential makes the device operate in conducting state. Therefore, the light-generated electrons and the electrons injected from the cathode region into channel can easily drift to the anode across the potential barrier by the pulling effect of anode voltage. The controlling effect of both gate potential and light irradiation cause the device conduct large anode current and work in conducting state. Therefore, a decrease in height of potential barrier in the channel resulted from the light irradiation lead to a reduction in anode voltage at which the negative resistance turn-around in *I*–*V* characteristics occurs.

4. Analysis and discussion

SIPTH exhibits different *I*–*V* characteristics for different bias voltages. In order to compare the simulation results with experimental results, assume the photon energy of the light is 1.5 eV, the flux of photons is 5×10^{15} cm$^{-2}\cdot$s^{-1}, the gate series resistance is 100 Ω，before discussing the influence of different resistances. The geometrical, technological and material parameters used in the simulation were expressed in section 2 and in Fig. 1. According to the impact of light irradiation on the device performances, the analysis process is divided into two: blocking state and conducting state.

4.1. Blocking-state

The channel between the cathode and the anode of SIPTH is pinched off by the depletion layer of reversely biased p$^+$n$^-$ junction. Figure 2 shows the potential distribution along the center line of channel in the blocking-state when the gate is biased with negative voltage (−3 V), and the positive

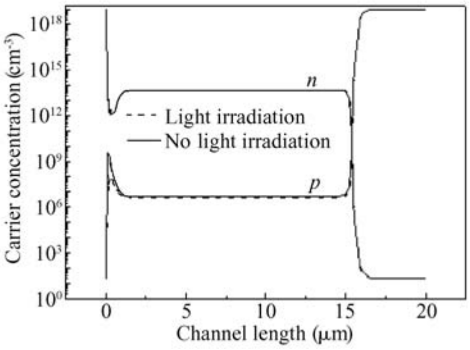

Fig. 3. Carrier concentration distribution in the equilibrium-state: (a) Light irradiation; (b) No light irradiation.

voltage (5 V) is applied to the anode.

A forward electric field in the direction from anode to the cathode in the channel is established by the anode voltage V_{AK}, and a reverse electric field is formed by the vertical component of that induced by the negative gate voltage V_{GK}. A minimum value of potential referred to as potential barrier with saddle shape is formed at X_0 point near the cathode end of channel by the interaction of the two electric fields opposite in direction. The potential barrier not only prevents the cathode electrons from drifting to the anode, but also prohibits the anode holes from penetrating the channel to reach the cathode. In order to switch the device from blocking state to conducting state, it is necessary to diminish the height of potential barrier either by decreasing the negative gate voltage V_{GK} or by increasing the positive anode voltage V_{GA}.

The electron-hole pairs are generated in the range of light penetration depth in the channel in the presence light irradiation. Thus, the effect of excess minority carriers in the channel is of significance. The concentration of light-induced holes in the channel between the cathode and saddle point X_0 is much higher than that of equilibrium holes. But the change in concentration of majority carrier electrons is not obvious as shown in Fig. 3. Most of the light-induced holes in the channel drift towards the gate biased to the lowest potential with accelerating velocity, forming gate photo-current, and the light-induced electrons drift mainly towards the anode. As the channel current in the blocking state is the reverse saturation current transmitted by the minority carriers, the current I_P formed by the light-induced minority carriers is much larger than that generated by equilibrium minority carriers when a light wave is incident on the surface of device. In this circumstance, the gate current can be expressed as

$$I_G = I_0 \left[\exp\left(\frac{eV_{GK}^*}{kT} \right) - 1 \right] - I_P, \tag{1}$$

where V_{GK}^* is the effective gate voltage at the intrinsic gate point, and I_P is the photocurrent that is directly proportional to the intensity of light irradiation.

4.2. Conducting state

When the anode voltage V_{AK} is gradually increased, the potential barrier in channel moves towards the cathode, and

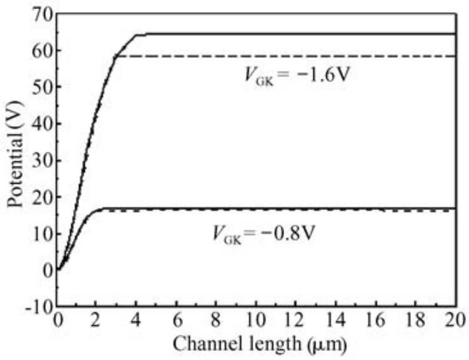

Fig. 4. Potential distribution along the channel in conducting-state.

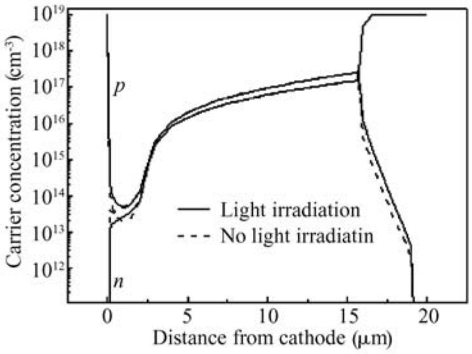

Fig. 5. Carrier concentration along center-channel in the conducting-state.

its height decreases continuously. When the height of potential barrier is reduced to a certain extent in the proximity of cathode, the concentration of electrons injected from the cathode into the channel increases. The potential distribution profile in channel is changed, and its height is further reduced by the mobile charges injected from cathode, as expressed in Eq. (2). With the increase in anode voltage V_{AK}, the potential barrier near the cathode vanishes, and the potential distribution in channel at the critical point at which the negative resistance turn-around will occur is shown in Fig. 4.

$$\nabla(-\varepsilon\nabla V) - q(p - n + C) = 0. \tag{2}$$

With the further increases in anode voltage V_{AK} and in electric field in lightly doped drift region, the transit time of holes, defined as the time for holes injected from anode to penetrate the channel to arrive at the cathode, decreases continually, and the concentration of holes increases gradually. When the anode voltage V_{AK} is increased to a certain critical value, the holes injected from the anode are able to completely transit the channel from the anode to cathode. Therefore, an electron–hole plasma of high concentration is built in channel and in drift region with light doping. The concentration distribution of carriers along the central line of channel for V_{GK} = −0.8 V in conducting state is shown in Fig. 5. When the transit time approaches the lifetime of excess minority carrier holes injected from the anode, the double injection results in the conversion from blocking state to conducting state.

In this situation, the concentrations of the electrons and holes injected from cathode and anode into the channel, respectively, are much higher than the concentrations of carriers

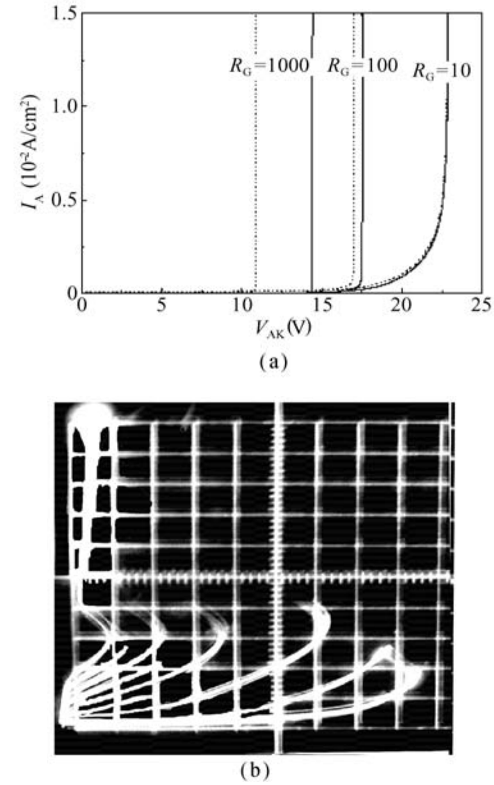

Fig. 6. I_A–V_{AK} characteristics for different gate resistances.

generated by light irradiation. The light irradiation does not significantly influence the distribution of carrier concentrations along the channel and double injection effect. However, the light irradiation can change transverse distribution of carrier concentration in gate-to-gate space near the surface, and increase the reverse saturation current of gate-cathode pn junction negatively biased. The effective gate voltage V^*_{GK} is changed by the increase in reverse saturation current flowing through gate series resistance, referred to as de-bias effect. Therefore, the negative resistance characteristics of device is indirectly impacted by de-bias effect given rise to by light irradiation. The effective gate voltage V^*_{GK} can be expressed as

$$V^*_{Gk} = V_{Gk} - I_G R_g, \tag{3}$$

where R_g is the gate series resistance, and I_G is the gate current expressed with Eq. (1).

The I_A–V_{AK} characteristics for given gate voltage V_{GK} = 0.8 V shown in Fig. 6(a) indicates that different gate series resistance results in different de-bias effects. The I_A–V_{AK} characteristics calculated by taking light irradiation into account is shown with dotted line, and the solid line indicates the I_A–V_{AK} characteristics computed by taking no account of light irradiation. It can be seen that for small gate series resistance such as R_g = 10 Ω, the effect of light irradiation on I_A–V_{AK} characteristics of device is ignorable. When R_g = 1000 Ω, the light irradiation can significantly influence I_A–V_{AK} characteristics, giving rise to a decrease in turn-around voltage from 14.40 to 10.88 V. It is demonstrated that the anode current of SITH is controlled by potential barrier in channel, instead of by gate current. The experimentally measured I_A–V_{AK} characteristics for different light irradiation intensity, shown in Fig. 6(b), approximately accords with theoretically calculated results shown in Fig. 6(a).

The de-bias effect of photocurrent formed by light-generated carriers through gate series resistance leads to a reduction in turn-around by decreasing the reversely biased voltage between gate and cathode. Since the height of potential barrier in the channel near the cathode is reduced by light-generated carriers, the anode voltage V_{AK} required to conduct the device becomes smaller.

5. Conclusions

The increase in gate current resulting from excess carriers generated by light irradiation incident onto the surface of device leads to the decrease in potential barrier height in the channel by means of de-bias effect of gate series resistance. Therefore, the device can be conducted by rather lower anode voltage V_{AK} than usual. It is important to optimally choose gate series resistance to acquire optimum light-control of SIPTH. The larger the gate series resistance is, the higher the controlling sensitivity of light irradiation is. However, too large gate series resistance will reduce photocurrent. The optimal value of gate series resistance 1000 Ω is obtained by theoretical analysis and experimental measurement for SIPTH with surface gate structure. The electron-hole plasma of high density established by the double–injection in cooperation with the de-bias effect of gate series resistance resulted from light irradiation makes SIPTH switch from blocking state to conducting state at lower anode voltage.

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