Infrared quenching operation of non-linear GaAs photoconductive semiconductor switch for terahertz generation

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Abstract: To use the non-linear GaAs photoconductive semiconductor switch (PCSS) with avalanche effect for terahertz generation, it is important to quench the photo-activated carrier domain (PACD) transporting in the semiconductor. In this work, a basic setup for quenching the non-linear GaAs PCSS was proposed which consists of two laser beams. The second laser beam was delayed about 100 ps for quenching the PACD after the first beam. In the experiments, the PCSS with 12 mm electrode gap can be biased up to 32 kV with 0.9 kA switching current. Good reproducibility of waveforms about 230 times at 20 kV is achieved with 14mm PCSS when trigger laser is orders of magnitude of tens milli-joules. Results show the process of infrared quenching non-linear mode could be operating repeatedly, which paves the way for future research of high power terahertz generation at high repetition rate.

Key words: GaAs; photoconductive semiconductor switch; non-linear mode; terahertz

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红外猝灭非线性砷化镓光电导开关产生太赫兹的实验研究

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摘 要: 在实验上对光激发电荷畴进行有效的猝灭,是利用具有雪崩倍增效应的非线性砷化镓光电导开关作为太赫兹辐射源的关键问题之一。提出了基于双光束红外激光来猝灭砷化镓光电导开关的非线性模式的初步实验方法,两束激光时延为 100 ps,其中第二束为猝灭光。实验中,12 mm 间隙的砷化镓光电导开关偏置电压可达到 32 kV,输出电流为 900 A。同时,14 mm 间隙开关在 20 kV 偏置、毫焦光能触发条件下,可连续工作 230 次,输出波形具有较好的重复性。结果表明,双光束红外激光能够猝灭非线性模式,重复工作性能稳定,对高重复频率触发下光电导方法产生高功率太赫兹辐射的研究奠定了前期实验基础。

关键词: 砷化镓; 光电导开关; 非线性模式; 太赫兹

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0 Introduction

Over the past decades, significant efforts have been focused on high power photoconductive semiconductor switches (PCSS). Photoconductive materials studied have included Si, GaAs, InP, ZnSe, and SiC. As the ideal candidate, GaAs has shown considerable promise performance due to its relative maturity of processing techniques, high dark resistance, high dielectric strength, fast recombination time, and the presence of non-linear or high gain mode. It should be noted that there are two distinctive operation modes for GaAs PCSS, i.e., linear and non-linear mode. When the bias electric field and energy of trigger laser is above a certain threshold value, the non-linear mode with carriers avalanche multiplication can produce as many as 10^3–10^5 electron-hole (e–h) pairs per absorbed photon, compared to linear PCSS, in which only one e–h pair is generated in per absorbed photon[1–6].

Essentially, the physical nature of the widely used terahertz (THz) photoconductive antenna (PCA) is the PCSS with electrode gap in the range of micrometers, in comparison to the gap size in the range of centimeters for high pulsed power applications such as compact repetition particle beam accelerators, optically activated electrical firesets. Presently, the utility of GaAs PCA for THz emission only depends on the operation of linear mode. On the contrary, non-linear mode featured with carriers avalanche multiplication, is especially important as it allows switching with significantly reduced laser light.

Up to now, there is no report that one uses GaAs PCSS operating with avalanche multiplication mode as THz emitter. To use the GaAs PCA with non-linear operation as intensive THz emitter, it is important to solve three key problems: (1) For higher THz emission using photoconduction with avalanche multiplication, the carriers avalanche multiplication mechanism in high electric field must be introduced to the linear mode of GaAs PCA, allowing forming the photoconduction with the feature of avalanche multiplication and radiating the intensive THz emission. (2) According to the conditions for avalanche multiplication mode, there is a big challenge for the present insulated protection and optimization of insulated structure, since the bias electric field would be high enough to breakdown the device when the excitation energy is only nano-joules (nJ) for single incident laser pulse. (3) Concerning the operation with high repetition rate of pump beams, transients of the long lock-on trailer in non-linear mode should be quenched in a certain time.

The goal mentioned above motivates us to design the preliminary experiment, which allows quenching the non-linear GaAs PCSS excited by infrared lasers. In other words, this device could operate not only with the carriers′ avalanche multiplication under high electric field, but also in the form of linear switching pulses without a long lock-on trailer.

1 Experiments

Experiments are performed based on semi-insulating (SI) GaAs which is grown by the Liquid Encapsulated Czochralski (LEC) technique. As shown in Figure 1, the PCSS consists of a 6-mm-wide and 0.6-mm-thick piece of SI GaAs. The resistivity in total darkness is larger than $5\times10^7\ \Omega\cdot cm$ and the mobility is larger than 5 500 $cm^2/(V\cdot s)$. The Au/Ge/Ni electrode forms ohmic contact by using a standard mixture of Ni/Au–Ge/Au for the metallization at 450 ℃. The electrode dimensions are $6\times3\ mm^2$ with a 500-nm-deep ledge has been etched with reactive ion etching and 800 nm thickness Si_3N_4 insulator layer is coated on the material. The SI GaAs PCSS mounted upside down on a ceramic sheet of high purity Al_2O_3 with microstrip line, is maintained in chamber with sulphur hexafluoride (SF_6) which is up to 3 atmospheres. The Nd:YAG nanosecond laser operated with 15 ns full width at half maximum laser pulse, at wavelength of 1 064 nm. Current flowing in the circuit was measured with a Rogowski coil, whose sensitivity and minimum response time are 0.1 V/A and 1 ns, respectively. The oscilloscope was TDS-5 054 and a 40 dB coaxial attenuator with a bandwidth of 1 GHz is used between the Rogowski coil and oscilloscope. The trigger laser pulses are reflected by a piece of quartz to make sure the intensity of laser is appropriate. This method actually results in two dependent trigger laser spot in the SI-GaAs sample due to the reflection of the upper and bottom surface of quartz, and the relative timing between the two laser pulses is about 100 ps based on the thickness of quartz. Those two dependent infrared lasers excite two samples, 12 mm and 14 mm gap sizes, respectively.

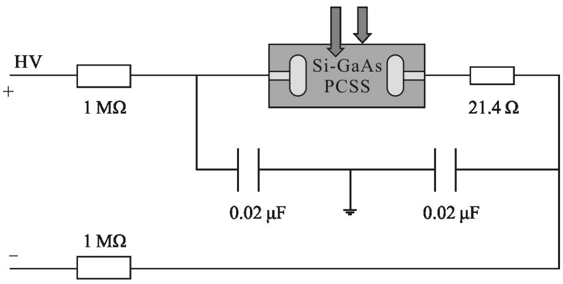

Fig.1 Schematic diagram of the testing circuit

2 Results and discussion

Figure 2 shows the characteristics of switching controlled by those dependent infrared lasers based on the samples with the 12 mm electrode gap. In this case, the maximum bias voltage can be up to 32 kV with 0.9 kA current switching. When the bias voltage is increased to 34 kV, breakdown of PCSS occurs due to surface flashover. Although the electric field and trigger laser energy meet the critical condition to occur nonlinear mode, somewhat surprising but interesting results appear repeatedly during the whole experiments, that there are no remarkable waveforms with characters of "lock-on". As we know, the criterion for high field domain formation is that the product of carrier's density and device length is larger than 10^{12} cm^{-2} in order for significant space charge to develop. Although carrier concentration in intrinsic SI GaAs material is extremely low[7], when the first laser triggered the sample, the density of photo-activated carriers can be above 10^{19} cm^{-3} called photo-activated charge (PAC). The threshold condition is met for negative differential resistance based and the electrons tend to "pile-up" where the electric field fluctuates above the threshold filed, the photo-activated charge domain(PACD) developed[3,7].

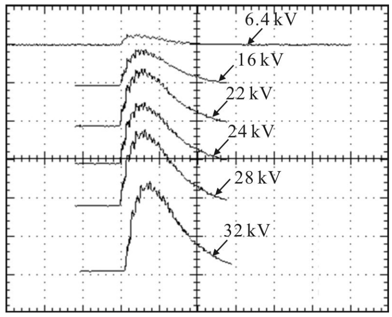

Fig.2 Superposed waveforms at different bias voltages (vertical axis: 20 A/V, 10 V/div; horizontal axis: 200 ns/div)

As Figure 3 shown, the simulated velocity of PAC remains saturated that indicates the PACD forms by order of magnitude of picoseconds following the bias voltage increasing, which shows good quantitative agreement with literature[7]. The re-absorption time τ_α can be expressed[6]:

$$\tau_\alpha=(\alpha\cdot c/\sqrt{\varepsilon_r})^{-1}\approx 10^{-14}\ \mathrm{s} \tag{1}$$

where $\alpha=5\times10^3$/cm, $c=3\times10^{10}$ cm/s is velocity of photon and $\varepsilon_r=13.18$ is the relative dielectric constant of GaAs material. Nucleation time (τ_R) of PACD is around 1 ps (see in Figure 3) above 20 kV bias voltages. Therefore, the numbers of domain in PCSS can be estimated theoretically:

$$N=l/(\tau_R\cdot v_s\cdot \tau_\alpha\cdot v_c)\approx 10^4 \tag{2}$$

where l the gap of electrodes distance, average velocity of the PACD is $v_s\cong 1\times10^7$ cm/s based on simulation and v_s is the velocity of photon within GaAs.

After about 100 ps, however, the second trigger laser pulse is incident while the early formed PACD have travelled about 10 μm with saturated velocity. Although the intensity of second laser is reduced slightly compared with the first laser, it also can initiate the photo-ionization with electric field from 13.0 kV/cm to 26.6 kV/cm, due to the native EL2 donor defect, and a new region with formation of PACD will occur. It implies that there are two regions present almost simultaneously in the GaAs in this setup. Even the unstable filaments are induced, they will strongly be diffused in two or more regions of the switch based on the lower limit of filaments width about 1–10 μm and the current density would be reduced significantly, allowing for higher bias operation.

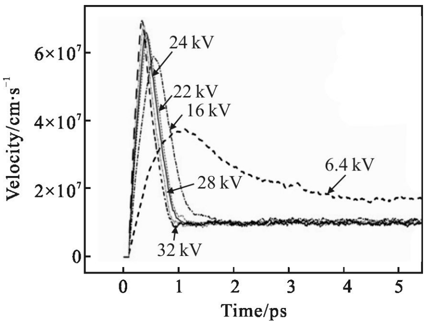

Fig.3 Simulation of the electrons average velocity at different bias voltages

During this process, extinction of PACD involves the competition among domains for the sustaining voltage, rather than for straightforward decrease in voltage below minimum maintained voltage [8–9]. As shown in Figure 2, the width of switching pulses is about 200 ns, which might be the result of the competition among domains. Another reason for width time of pulses is higher than that of regular lock-on is similar to the phenomena we discussed previously [10]. The hold-off characteristics of the 14 mm sample is apparently reduced when triggered in the manner mentioned above, after 239 times shots at 20 kV. Figure 4 shows the superposed waveforms of the second sample in longevity experiments based on the sample of 14 mm, the maximum current is about 414 A.

It is well known that the electric field of THz radiation can be expressed as:

$$E_{\mathrm{THz}} \propto ev\frac{\partial n}{\partial t}+en\frac{\partial v}{\partial t} \tag{3}$$

And the amplitude of THz radiation originating from the carrier density change is much larger than that of THz radiation proportional to carrier acceleration. The amplitude of THz radiation originating from carrier acceleration in nonlinear mode of photoconductive antenna is larger than that in linear mode. Thus, there would be intensive THz radiation originating from the carrier density change caused by avalanche multiplication mechanism.

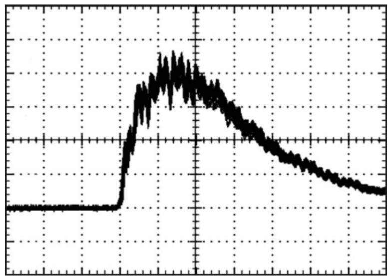

Fig.4 Superposed (230 times) switching waveforms of the second sample biased at 20 kV (vertical axis: 10 A/V; horizontal axis: 80 ns/div)

3 Conclusion

For extending non-linear mode of GaAs to THz technology, we design a primary setup based on GaAs PCSS. Bias voltage can be up to 32 kV with 0.9 kA switching current and good reproducibility of waveforms about 230 times at 20 kV is achieved and results show the process could be performed repeatedly. However, the excitation energy is still high compared with fs laser beam of nJ. A higher voltage standoff performance for PCSS needs to be solved as to keep the device operating at a repetition rate up to ~80 MHz. Several subsidiary methods should be prepared such as using the external capacitance quenching, vertical electrodes fabrication that we are attempting to investigate.

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