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# Saturability Algorithm of a Sub-Bandgap Laser for Triggering a Photoconductive Switch

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**ABSTRACT** Based on the experimental comparison of a GaN photoconductive semiconductor switch (PCSS) and two GaAs PCSSs, it is proposed that PCSSs made on heavily compensated substrates without the obvious optical frequency-doubling effect possess the laser-energy saturation threshold when triggered with a sub-bandgap laser. To this sort of PCSS, an algorithm is proposed for predicting the laser-energy saturability curves and the relevant saturation thresholds varying with the wavelength of a sub-bandgap laser. The algorithm is verified using the GaN:Fe PCSS experiment data.

**INDEX TERMS** Photoconductive switch, saturation, sub-bandgap, GaN, GaAs.

## I. INTRODUCTION

A PCSS operating in the linear mode [1], [2] triggered with an ultra-fast power pulsed laser system is the best option to simultaneously meet the needs of low triggering-jitter, ultra-broadband, high power and electromagnetic interference (EMI) mitigation, especially when it is made on the substrate with short carrier lifetime and high carrier mobility, such as GaAs and GaN [3]–[6]. Recently, the usage of the sub-bandgap laser is getting enhanced attention, because it not only relieves the current crowding and the flashover on the surface of a traditional lateral PCSS, but also dramatically reduces the cost and the volume of the laser system of a wide-bandgap PCSS [2], [6]. It is known that the amplitude fluctuation of power pulsed lasers is generally more than 5%, and the jitter of the photocurrent-pulse peak values of PCSSs is mainly caused by the inevitable amplitude fluctuation of the laser energy [7]. If there exists a laser-energy saturation threshold of the two-photon absorption response to the PCSSs triggered by a sub-bandgap laser, the laser-energy supersaturation will keep the photocurrent peaks greatly stabilized [8], [9]. However, for a laser with a certain wavelength in a certain operation mode, the higher demand on the single-pulse laser-energy maximum usually means the higher cost, the greater volume and the heavier weight of the laser. The cost and the portability of the whole photoconductive switch system depend mainly on those of the laser. Therefore, the photoelectric-transformation saturation depth (i.e., laser-energy saturability mentioned in this paper) is an important parameter to optimize the laser energy for reaching the best balance between the photocurrent-peak stability, the cost, and the system portability.

Regarding the two-photon absorption response in PCSSs, there are two physical mechanisms: one is the two-photon simultaneous absorption due to the optical frequency-doubling (OFD) effect caused by the second harmonic of nonlinear optics [10], [11], such as in GaAs or $LiNbO_3$ frequency doubling crystals; the other is the two-step photon absorption via a deep energy level in the forbidden band regarding as a "ladder" to the photon-excited electrons, such as the iron energy levels in GaN:Fe PCSSs or the vanadium energy levels in SiC:V PCSSs [2], [8]. In this paper, first it is discussed which sort of PCSSs can possess the laser-energy saturation threshold if triggered by a sub-bandgap laser, through experimentally comparing a GaN:Fe PCSS without the OFD effect and two GaAs:EL2 PCSSs with the obvious OFD effect. Next, only to the sort of PCSSs without the OFD effect, an algorithm is proposed for predicting the laser-energy saturability and the relevant saturation threshold varying with the wavelength of the sub-bandgap laser.

## II. COMPARATIVE EXPERIMENTS

Two GaAs PCSSs were fabricated on a 0.6-mm-thickness piece of unintentionally-doped (100) GaAs substrate grown with the liquid-encapsulated czochralski method.

The Au/Ge/Ni alloy electrodes are of ohmic contact and the plain size of each electrode is 6.0 mm $\times$4.0 mm. The electrode distance from the anode to the cathode of a PCSS is called the electrode gap. The electrode gaps of the two PCSSs are 0.5 mm and 1.5 mm, respectively. The measurement circuit is demonstrated in Fig. 1. The 0.5-mm-gap and the 1.5-mm-gap PCSSs are biased at 5 V and 11.7 V (i.e., 100 V/cm and 78 V/cm), respectively. The electron mobility of the substrate is approximately above 5500 $cm^2/(V\cdot s)$. The two GaAs PCSSs are tested with a 7-ns-pulsewidth 1064-nm-wavelength Nd:YAG laser, and the relevant photocurrent waveforms are demonstrated in Fig. 2. The relationship curves of the photocurrent-pulse peak values and the single-pulse laser energy are measured as shown in Fig. 3. It is noted that, there is an energy level of 0.76 eV below the GaAs conduction band, named EL2, caused by the $V_{Ga}$-$As_{Ga}$-$V_{Ga}$ point defects [12]. When the GaAs crystal growing, the unintentionally-introduced shallow acceptors (such as C on As-site) are highly compensated by the unintentionally-introduced EL2 deep donors, which is called self-compensation mechanism and leads to the high substrate resistivity (more than $5\times10^7\cdot\Omega$ cm). The EL2 levels are the dominant ladders to the two-step photon absorption when triggered with a sub-bandgap laser, since the EL2 concentration is about $2\times10^{16}$ $cm^{-3}$.

The 10-mm-gap GaN PCSS, fabricated by the Kyma Technologies, Inc., is made on a piece of freestanding wurtzite GaN substrate [6]. The substrate is grown on the lattice buffer layers from the (0001) sapphire $Al_2O_3$ to the AlN, with the hydride vapor phase epitaxy (HVPE) method [13]. It is noted that, iron ions with the concentration of about $10^{18}$ $cm^{-3}$ have been doped when the GaN crystal growing, as a sort of deep-energy-level acceptor to compensate the unintentionally-introduced shallow donors mainly due to the O-on-N-sites, Si-on-Ga-sites and N-vacancies [14], [15]. The Fe heavy doping not only makes the substrate resistivity more than $1\times10^9\Omega\cdot$cm, but also brings the abundant deep energy levels for the two-step photon absorption of the GaN PCSS triggered with a sub-bandgap pulsed laser. The electron mobility is about $3\times10^2$ $cm^2/(V\cdot s)$ and the bias voltage is 1 kV (i.e., its electric field is 1 kV/cm), so the average drift velocity of the photo-generated electrons in the GaN:Fe PCSS is as the same order of magnitudes, $10^5$cm/s, as those in the two GaAs:EL2 PCSSs. The experiment circuit and the measurement results have been reported in [6]. The data points on the relationship of the photocurrent-pulse peak values and the single-pulse laser energy are demonstrated in Fig. 4. Moreover, 12 data points on the extrinsic absorption coefficient of the GaN:Fe PCSS substrate material are demonstrated in Fig. 5.

## III. ANALYSIS AND DISCUSSION

In the GaN:Fe PCSS experiment, there is an obvious laser-energy saturation threshold at about 1.55 mJ (see Fig. 4). It means that, when the laser energy is more than the threshold the On-state resistance of the PCSS device is not able to continue decreasing with the laser energy increasing. The On-state resistance closely depends on the photon absorption amount of the PCSS operating in linear mode [2] when the conditions of the laser and the bias electric field hold changeless. GaN is regarded as a material without the OFD effect in general engineering applications. The two-photon absorption response to the GaN PCSS is of the two-step photon absorption through the Fe deep energy levels in the forbidden band. When the deep energy levels in the light path of the PCSS have been used up, the photocurrent-pulse peak does not keep increasing with the laser energy.

In the GaAs:EL2 PCSS experiment, there is no laser-energy saturation threshold but there is an obvious curve inflection point at about 0.17 mJ (see Fig. 3). When less than the curve inflection point, the peak-value increasing with the laser-energy is rapid, because both the two-step photon absorption (due to the EL2 deep energy levels) and the two-photon simultaneous absorption (turning every two 1064-nm-wavelength photons into a 532-nm-wavelength photon) are working. When more than the curve inflection point, the peak-value increasing with the laser-energy is slow, because the EL2 deep energy levels on the light path have been used up for the two-step photon absorption. Therefore, the subsequent slow increment is only contributed by the OFD effect. Theoretically, the increment due to the OFD effect will continue until the concentration of the photo-generated carriers has reached up to make the carrier mobility

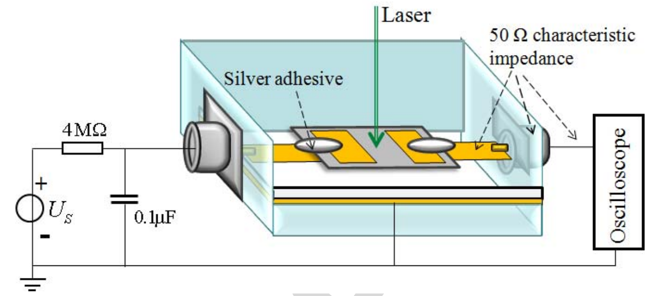


**FIGURE 1.** Schematic diagram of the GaAs PCSS experimental circuit. The Au/Ge/Ni ohmic electrodes of the PCSS are connected to the microstrips made on a copper-clad $Al_2O_3$ plate.

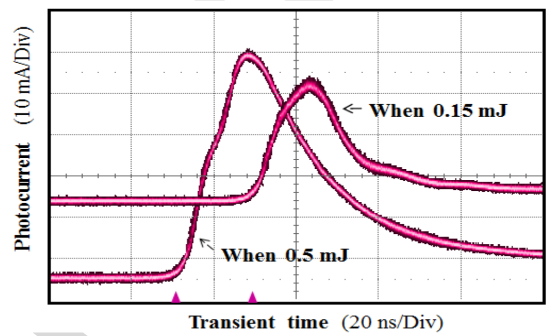


**FIGURE 2.** 20-time-overlap photocurrent waveforms of the 1.5-mm-gap GaAs PCSS biased at 78 V/cm triggered with a 7-ns-pulsewidth 1064-nm-wavelength Nd:YAG laser.

greatly decreased due to the Coulomb scattering effect or has reached up to that the substrate is unable to absorb more photons due to the spectral hole burning effect [16], [17] based on the Pauli's exclusion principle.

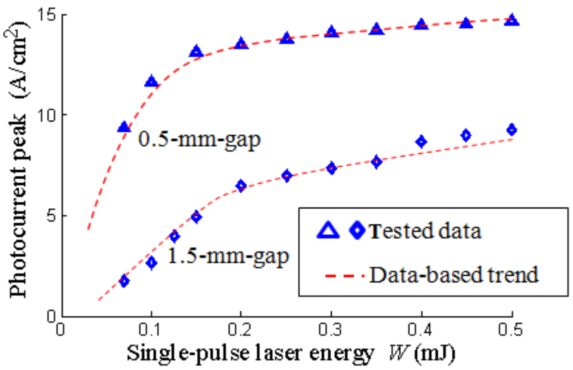


**FIGURE 3. Relationship of the photocurrent-pulse peak values of the GaAs PCSSs and the single-pulse energy of the 7-ns-pulsewidth 1064-nm-wavelength laser. The 0.5-mm-gap and the 1.5-mm-gap PCSSs are biased at 100 V/cm and 78 V/cm, respectively. Every data point of the GaAs experiment is the mean value of 20 times measurement.**

Through the above experimental comparison, it is proposed that, PCSSs made on heavily-compensated substrates without the ODF effect can possess the laser-energy saturation threshold when triggered with a sub-bandgap laser. For this sort of PCSS, an algorithm on saturability and threshold is proposed in the following.

The optical intensity distribution along the incident direction ($z$) in a PCSS is given by the following:

$$I(z) = I_{(z=0)}\exp^{-\alpha z} \tag{1}$$

where $\alpha$ is the absorption coefficient of the PCSS substrate crystal. To a heavily-compensated substrate without the OFD effect, there is a dominant deep energy level and only the two-step photon absorption via the dominant deep level needs to be considered. Therefore, the optical absorption coefficient to sub-bandgap wavelength ($\lambda$) is given by

$$\alpha(\lambda) = \mathrm{In}\left[\frac{m(\lambda)}{m(\lambda) - N_d}\right] \text{ when } \lambda < \frac{1.24\ \mu\text{m}\cdot\text{eV}}{\max(E_d,\ E_g - E_d)} \tag{2}$$

where $m$ is the photon amount of an incident laser pulse per unit light path, $N_d$ is the effective amount of the dominant deep energy level per unit light path, $E_g$ is the forbidden-band width and $E_d$ is the dominant deep energy level below the conduction band of the substrate material.

In the case of the GaN:Fe PCSS, the $Fe^{3+}$ energy level is dominant among all kinds of the two-step photon-absorption ladders, because its density is at least two orders of magnitude higher than the other energy-level densities of the shallow donors and acceptors [18]. Since the $Fe^{3+}$ level is 1.299 eV [18] below the conduction band of GaN and the GaN forbidden bandwidth is 3.42 eV, the upper limit of the laser wavelength for the two-step photon absorption is about 585 nm (i.e., 3.42eV minus 1.299 eV) based on (2).

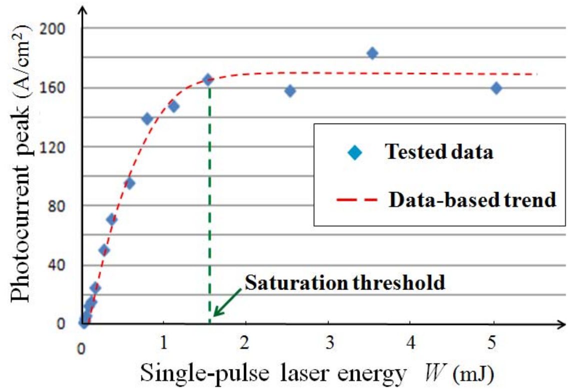


**FIGURE 4. Relationship of the photocurrent-pulse peak values and the single-pulse laser energy when triggering the GaN:Fe PCSS with the bias electric field of 1 kV/cm, the laser pulsewidth of 5 ns and the wavelength of 532 nm [6].**

When measuring the $\alpha(\lambda)$ curve of substrate materials, usually the laser single-pulse energy ($W$) and the pulsewidth are constant. Supposing this used laser energy as $W_0$, the two parameters in (2) can be given by

$$m(W,\lambda) = \frac{W}{2\mathrm{hc}/\lambda}\ ,\ N_\mathrm{d} = \frac{W_0}{2\mathrm{hc}/\lambda_\mathrm{d}} \tag{3}$$

where $h$ is the Planck constant, $c$ is the speed of light in vacuum, and $\lambda_d$ is the effective wavelength just making the crystal absorption of unit light path critically saturated. Based on (2) and (3), the absorption coefficient is deduced to be

$$\alpha(\lambda) = \mathrm{In}\left(\frac{\lambda}{\lambda - \lambda_\mathrm{d}}\right). \tag{4}$$

Based on (4) and a few of absorption-coefficient experimental data points (such as the points shown in Fig. 5), the value of $\lambda_d$ can be obtained using the curve-fitting method. Based on (3), the laser-energy saturability of the PCSS varying with the energy and the wavelength of the triggering laser is given by

$$\eta(W,\lambda) \overset{def}{=} \frac{m(W,\lambda)}{N_d} = \frac{W\lambda}{W_0\lambda_d}. \tag{5}$$

The saturation threshold is the laser-energy value at $\eta$=100%.

In the case of GaN:Fe PCSS, the value of $\lambda_d$, 405.996 nm, is calculated out using the curve-fitting method based on (4) with the experimental data of Fig. 5. The effectiveness of the curve fitting is demonstrated in Fig. 5, which standard deviation is 0.11 cm$^{-1}$. The curve fitting deviation slightly increases after the wavelength is greater than 500 nm, because the thermal absorption effect is ignored in the above equations. Base on (5) and the $\lambda_d$ value above, the saturability curves of the GaN:Fe PCSS varying with laser energy under different wavelengths are calculated and the results are shown in Fig. 6. Therefore, the laser-energy saturation threshold of the GaN:Fe PCSS triggered by a 5-ns-pulsewidth

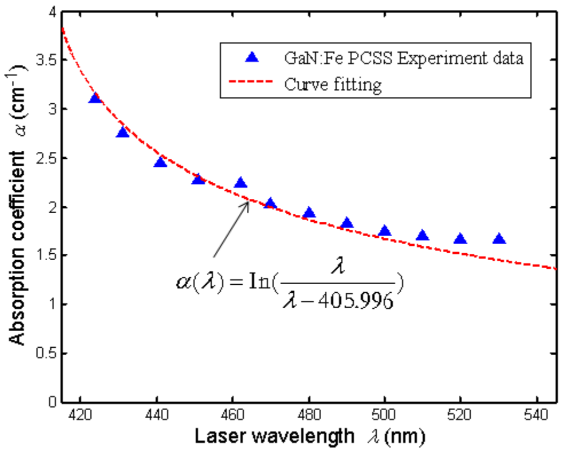


**FIGURE 5. Absorption coefficient curve of the GaN:Fe PCSS substrate material. The 12 data points of absorption coefficient are measured using a frequency tripled line (355 nm) of the 5-ns-pulsewidth laser and an optical parametric oscillator (OPO) to vary the wavelength of the output light. Note that the laser energy illuminating on the substrate material is always 2 mJ to each wavelength of the 12 data points [6]. The red-color dashed curve is fitted based on (4) using the 12 data points.**

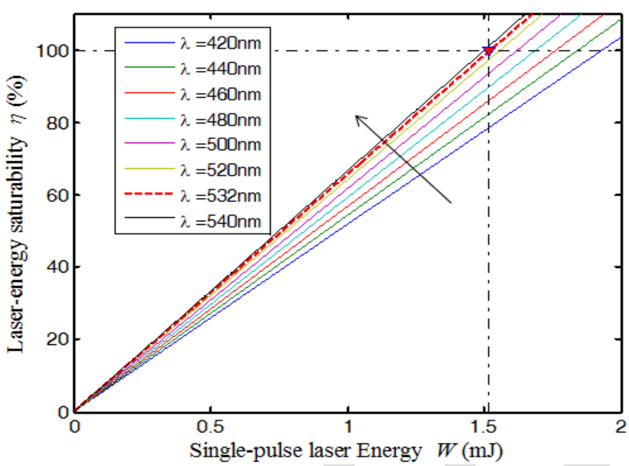


**FIGURE 6. Laser-energy saturability of the GaN:Fe PCSS. The curves are calculated, based on (5) where $\lambda_d$= 405.996 nm and $W_0$ = 2 mJ. The '$\nabla$' symbol marks the predicted saturation threshold when the PCSS is triggered with a 5-ns-pulsewidth 532-nm-wavelength laser.**

sub-bandgap laser can be predicted. As shown in Fig. 6, the calculated laser-energy threshold should be 1.52 mJ when the laser wavelength is 532 nm, which calculated threshold is in approximate agreement with the measured threshold of the GaN PCSS experiment shown in Fig. 4.

## IV. CONCLUSION

Through experimentally comparing the GaN:Fe PCSS and the GaAs:EL2 PCSSs, it is demonstrated that there exists a laser-energy saturate threshold to a PCSS if the PCSS triggered with a sub-bandgap laser is made on a heavily-compensated substrate without the obvious ODF effect. Furthermore, to such sort of PCSS an algorithm is proposed for predicting the photoelectric-transformation saturation depth varying with the laser energy and the relevant saturation threshold under different wavelength conditions. The prediction method only needs to actually measure a few of data points on the absorption coefficient curve of the PCSS's substrate material, using a laser that has the same energy and the same pulsewidth as those of the laser triggering the PCSS. The prediction is relatively simple but is helpful to design a PCSS system with a good balance between the photocurrent-peak stability, the cost and the portability.

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