A GaN-Based Insulated-Gate Photoconductive Semiconductor Switch for Ultrashort High-Power Electric Pulses

Xinmei Wang, Member, IEEE, Sudip K. Mazumder, Senior Member, IEEE, and Wei Shi

Abstract—For monolithic realization of a traditional photoconductive semiconductor switch (PCSS) incorporating a high-voltage pulsed bias, an insulated-gate photoconductive semiconductor switch (IGPCSS) structure is proposed. The insulated-gate cells in this structure can aid the laser-triggered area to dynamically obtain a much higher bias voltage than the dc withstand voltage of a traditional PCSS. The static and the dynamic characteristics of a GaN-based IGPCSS triggered by a subbandgap laser are analyzed, and the results show that its photoelectric-conversion efficiency is twice that of a dc-charged traditional GaN-based PCSS for same triggering conditions.

Index Terms—Photoconductive switch, pulsed power, MISFET, GaN.

I. INTRODUCTION

A PHOTOCONDUCTIVE semiconductor switch triggered with an ultra-short pulsed laser is a type of low-jitter ultra-broadband high-power device without potential spurious triggering caused by electro-magnetic interference (EMI) [1], [2]. To avoid the use of expensive ultraviolet laser, the wide-band-gap PCSS is usually made of highly-compensated semi-insulating material with sub-bandgap absorption ability, such as GaN:Fe [3] or SiC:V [4]. However, its dark-state current characteristic is remarkably nonlinear, which is mainly caused by the unavoidable high-concentration deep energy levels. It is known that, a high-voltage pulsed source, such as a Marx circuit [5], can significantly improve the device lifetime and the photoelectric response [6], but it also leads to higher cost and problem with portability, especially when high repetition rate is required.

Therefore, it is necessary to design a novel PCSS with an electric power switch structure vertically integrated to share the dc-bias voltage. Considering that the repetition rate of a traditional PCSS can reach up to hundreds of megahertz, the structure of multi-cell U-shape n-channel MISFET is the best selection to the design of the novel PCSS. In this letter, the design principles are presented, the voltage and the current formulas are deduced, and the expected effect is validated through the simulation of a relevant GaN-based device sample.

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Fig. 1. a) Lateral view of the GaN-based IGPCSS. b) Equivalent circuit model of the IGPCSS device (middle), illustrating the schematic diagrams of a bias source (left) and the timing sequence of trigger signals (right).

II. DESIGN

A. IGPCSS Structure and Triggering Method

The insulated-gate PCSS structure is illustrated in Figs. 1a and 2. The U-shaped MISFET cells are fabricated in the GaN epitaxy layers which grow on a semi-insulating GaN:Fe substrate. The unintentionally-introduced shallow donor levels in the GaN substrate result from the O on N-sites, Si on Ga-sites and N-vacancies [7], [8]. The iron impurities, as deep acceptor sources, are intentionally heavy doped (~10^{18} cm^{-2}) to compensate the shallow donors for making the substrate dark resistivity up to 1 × 10^9Ω · cm, and meanwhile the substrate carrier lifetime sharply decreases to < 1ns [3]. A gate-voltage pulse makes the channel entirely open and then two rows of 1-ns-pulsewidth 1-mJ-energy 532-nm-wavelength laser beams simultaneously illuminate the semi-insulating substrate from opposing sides. The equivalent circuit model composes of a traditional PCSS, an n-channel normally-closed MISFET, and a voltage-stabilizing diode, as illustrated in Fig. 1b.

A few of methods are used to increase the safe operating area of the IGPCSS. The laser fibers are grouped into two rows, and the directions of the laser beams are interdigitated each other (see Fig. 2) to prevent the current crowding happened in the laser-triggered area. The multi-cell parallel connection and the light-doping transition (see n_3 and
n\textsubscript{4} layers) for the n-channels terminals are designed to prevent the current crowding enhanced in the gate-triggered area. Furthermore, the chamfer processes is helpful to improve the blocking voltage ability of the gate-triggered area.

B. Static Voltage Distribution

The static distribution of the electric field across the IGPCSS before it is triggered by an electrical gate signal is shown in Fig. 3. The space charges in the n\textsubscript{1} layer can be ignored due to the semi-insulating property, and hence the electric field across the n\textsubscript{1} layer in the y direction (E\textsubscript{1}) is regarded as a constant. The voltage drop due to the bulk resistances of the n\textsubscript{2}, p, n\textsubscript{0} layers can be ignored, since their conductivities are much higher than that of the semi-insulating substrate. Moreover, the voltage drop across the positively biased p-n\textsubscript{4} junction can be ignored when the IGPCSS is biased with high voltage. Therefore, through integrating the electric field curve of Fig. 3, the static voltage across the gate-triggered area is given by

\[ V_{th} = k \left[ \frac{q}{\varepsilon} \left( \frac{p d_p^2}{2} + \frac{n_3 d_1^2}{2} + n_2 d_2 d_3 + \frac{n_3 d_2^2}{2} \right) + E_1 (d_2 + d_3) \right] \]

In (1), \( q \) is the elementary charge, \( \varepsilon \) is the dielectric constant of the epitaxial material, and \( k \) (\(<1\)) is a semi-empirical coefficient which is used to linearly simplify the effect caused by the x-directed extension of the carrier-depleted region along the insulated gate. It is noted that, the thickness of the p-type epityx layer \((d_p)\) in the Fig. 1 should be more than the minimum design value \((d'_p)\), or the pn\textsubscript{4} junction will be punched through undesirably from the cathode side. Equation (1) yields that \( V_{th} \) will monotonically slightly change following the bias voltage and the substrate thickness, as shown in Fig. 4.

C. Photocurrent Distribution

To design the relevant heat-dissipation accessory of the IGPCSS, the photocurrent distribution in the x direction is estimated roughly. The density of the gallium-site Fe\textsuperscript{3+} deep energy level is much higher than those of any other energy levels in the GaN:Fe [8]. It means that the two-step photon absorption from valence band to conduction band via the Fe\textsuperscript{3+} levels is dominant, if the laser wavelength is less than 585 nm (i.e., 3.42 eV-1.299 eV [8]). Therefore, the optical intensity distribution in the IGPCSS can be given by

\[ I(x, t) = I_0 \left[ e^{-\alpha_{eff} x} + e^{-\alpha_{eff} (L-x)} \right] G(t). \] (2)

In (2), \( I_0 \) is the initial optical intensity of the incident laser only from one side of the IGPCSS, \( G \) is a Gaussian function, and \( \alpha_{eff} \) is the effective absorption coefficient to linearly simplify the two-step photon absorption via the high-density deep energy levels [3]. Considering that the cost of the power pulsed laser device is typically incorporated in the total cost of the switch system, the lost laser energy transmitted from the opposite sides of the IGPCSS is expected to be less than 5% of the incident energy. The x-directed device length \( L \) can be roughly estimated based on (2).

The rate for the photon-generated electrons \((n)\) in the semi-insulating GaN substrate is given by

\[ \frac{\partial n(x, t)}{\partial t} = -\frac{1}{2\hbar \omega} \frac{\partial}{\partial x} \left( n(x, t) \right) \frac{\partial I(x, t)}{\partial x} - \frac{n(x, t)}{\tau_r}, \] (3)

where \( \hbar \omega \) is the photon energy and \( \tau_r \) is the effective recombination rate. Therefore, the peak electron density is deduced by setting \( \frac{\partial n(x, t)}{\partial t} = 0 \) to obtain the following:

\[ n(x, t_{peak}) = \frac{\tau_r \alpha_{eff}}{2\hbar \omega} I(x, t_{peak}) \] (4)

where \( I(x, t_{peak}) \) is obtained using (2). The peak conductivity is given by

\[ \sigma(x, t_{peak}) = q n(x, t_{peak}) (\mu_n + \mu_p) \] (5)
ub, linear range (i.e., below 200 kV/cm for the wurtzite 
the IGPCSS laser-triggered area is still in the velocity-field 
where \( \mu \) and \( n \times p \) are the electron and the hole mobilities, 
respectively. The current density is proportional to the 
conductivity, which results in 

\[
J(x, t_{peak}) \propto e^{-\mu_{eff}x} + e^{-\mu_{eff}(L-x)}.
\]  

(6)

III. Analysis and Comparison

The static voltage distributions are simulated using 
Silvaco [9] and the results are shown in Fig. 5. The voltage 
across the gate-triggered area slightly decreases with \( d_{1} \) and 
slightly increases with \( U_{b} \). These variations are in agreement 
with the above conclusions calculated based on (1). It is noted 
that, the voltage across the gate-triggered area is approxi-
matively a constant, which validates the equivalent circuit 
model of the IGPCSS in Fig. 1b. Therefore, there exist two 
thresholds for the IGPCSS device to output photocurrents: one, 
which represents the gate voltage when the n-channels are just 
formed; and the other, which represents the bias voltage when 
the p-n junction is just punched through.

Next, the leakage current and the transient characteristics of 
an IGPCSS with a punch-through voltage of 400 V are simu-
lated. The simulation model and the results are shown in Fig. 6. 
With the IGPCSS being electrically triggered by the gate, the 
voltage across the gate-triggered area is gradually transferred 
to the laser-triggered area (see the orange curve in Fig. 6c), 
which enhances the electric field across the IGPCSS 
laser-triggered area from 6.7 kV/cm to 13.4 kV/cm.

Third, a comparable traditional PCSS (CT-PCSS) model 
(see Fig. 6b) are simulated, which have the same material, 
size, ohmic electrodes, static electric field and laser as that 
of the IGPCSS. The result demonstrates that the leakage 
current of the IGPCSS is far less than that of the CT-
PCSS owing to the p-n junction. Furthermore, the results 
demonstrate that the IGPCSS yields higher photocurrent peaks 
than the CT-PCSS. The photoelectric-conversion efficiency 
of the IGPCSS \((\eta_{IG})\) is higher than that of the CT-PCSS 
\((\eta_{CT})\). The photoelectric-conversion efficiency is referred 
in this letter as the ratio of the output photocurrent peak and 
the relevant input single-pulse laser energy. The efficiency 
increment \((\eta_{IG} - \eta_{CT})\) is approximatively proportional to 
\( U_{b}/(U_{b} - V_{th}) \) if the enhanced transient electric field across 
the IGPCSS laser-triggered area is still in the velocity-field 
linear range (i.e., below 200 kV/cm for the wurtzite 
GaN material used [10]). Considering \( V_{th} \) is almost 
a constant for varying \( U_{b} \), it is concluded that, the 
photocurrent of IGPCSS can be controlled relatively easily by varying the dc-bias voltage.

IV. Conclusion

A novel insulated-gate photoconductive semiconductor 
switch (IGPCSS) structure is presented. It attains a monolithic 
integration of a PCSS and MISFET cells thereby yielding 
less leakage current and higher photoelectric-conversion 
efficiency compared to a relevant traditional PCSS. Through 
the simulation analyses of the static and the dynamic charac-
teristics, the GaN-based IGPCSS design is validated.

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$$E_{\text{dark}} = \frac{q}{\varepsilon} \left( \frac{p d_p^2}{2} + \frac{n_3 d_2^2}{2} + n_2 d_2 d_3 + \frac{n_3 d_2^2}{2} \right) + E_1 \left( d_2 + d_3 \right) + E_2 \left[ d_1 - d_4 - d_3 \right].$$

In (1), \(q\) is the elementary charge, \(\varepsilon\) is the dielectric constant of the epitaxial material, and \(k\) (<1) is a semi-empirical coefficient which is used to linearly simplify the effect caused by the \(x\)-directed extension of the carrier-depleted region along the insulated gate. It is noted that, the thickness of the \(p\)-type epitaxy layer \(d_p\) in the Fig. 1) should be more than the minimum design value \((d'_p)\), or the \(p-n\) junction will be punched through undesirably from the cathode side. Equation (1) yields that \(V_{th}\) will monotonically slightly change following the bias voltage and the substrate thickness, as shown in Fig. 4.

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$$I(x, t) = I_0 \left[ e^{-a_{\text{eff}} L} + e^{-a_{\text{eff}} (L-x)} \right] G(t).$$

(2)

In (2), \(I_0\) is the initial optical intensity of the incident laser only from one side of the IGPCSS, \(G\) is a Gaussian function, and \(a_{\text{eff}}\) is the effective absorption coefficient to linearly simplify the two-step photon absorption via the high-density deep energy levels [3]. Considering that the cost of the power pulsed laser device is typically incorporated in the total cost of the switch system, the lost laser energy transmitted from the opposite sides of the IGPCSS is expected to be less than 5% of the incident energy. The \(x\)-directed device length \((L)\) can be roughly estimated based on (2).

The rate for the photon-generated electrons \((n)\) in the semi-insulating GaN substrate is given by

$$\frac{\partial n(x, t)}{\partial t} = - \frac{1}{\hbar \omega} \frac{\partial I(x, t)}{\partial x} - \frac{n(x, t)}{\tau_r}$$

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where \(\hbar \omega\) is the photon energy and \(\tau_r\) is the effective recombination rate. Therefore, the peak electron density is deduced by setting \(\frac{\partial n(x, t)}{\partial t} = 0\) to obtain the following:

$$n(x, t_{\text{peak}}) = \frac{\tau_r a_{\text{eff}} I(x, t_{\text{peak}})}{\hbar \omega}$$

(4)

where \(I(x, t_{\text{peak}})\) is obtained using (2). The peak conductivity is given by

$$\sigma(x, t_{\text{peak}}) = q n(x, t_{\text{peak}}) (\mu_n + \mu_p)$$

(5)
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\[ \eta = \frac{P_{out}}{P_{in}} \]

where \( \mu_n \) and \( \mu_p \) are the electron and the hole mobilities, respectively. The current density is proportional to the conductivity, which results in

\[ J(x, t_{peak}) \propto \left[ e^{-\alpha_{eff}x} + e^{-\alpha_{eff}(L-x)} \right]. \] (6)

### III. Analysis and Comparison

The static voltage distributions are simulated using Silvaco [9] and the results are shown in Fig. 5. The voltage across the gate-triggered area slightly decreases with \( d_1 \) and slightly increases with \( U_B \). These variations are in agreement with the above conclusions calculated based on (1). It is noted that, the voltage across the gate-triggered area is approximatively a constant, which validates the equivalent circuit model of the IGPCSS in Fig. 1b. Therefore, there exist two thresholds for the IGPCSS device to output photocurrents: one, which represents the gate voltage when the n-channels are just formed; and the other, which represents the bias voltage when the p-n junction is just punched through.

Next, the leakage current and the transient characteristics of an IGPCSS with a punch-through voltage of 400 V are simulated. The simulation model and the results are shown in Fig. 6. With the IGPCSS being electrically triggered by the gate, the voltage across the gate-triggered area is gradually transferred to the laser-triggered area (see the orange curve in Fig. 6c), which enhances the electric field across the IGPCSS laser-triggered area from 6.7 kV/cm to 13.4 kV/cm.

Third, a comparable traditional PCSS (CT-PCSS) model (see Fig. 6b) are simulated, which have the same material, size, ohmic electrodes, static electric field and laser as that of the IGPCSS. The result demonstrates that the leakage current of the IGPCSS is far less than that of the CT-PCSS owing to the p-n junction. Furthermore, the results demonstrate that the IGPCSS yields higher photocurrent peaks than the CT-PCSS. The photoelectric-conversion efficiency of the IGPCSS (\( \eta_{IG} \)) is higher than that of the CT-PCSS (\( \eta_{CT} \)). The photoelectric-conversion efficiency is referred in this letter as the ratio of the output photocurrent peak and the relevant input single-pulse laser energy. The efficiency increment (\( \eta_{IG} - \eta_{CT} \)) is approximatively proportional to \( U_B/(U_B-V_{th}) \) if the enhanced transient electric field across the IGPCSS laser-triggered area is still in the velocity-field linear range (i.e., below 200 kV/cm for the wurtzite GaN material used [10]). Considering \( V_{th} \) is almost a constant for varying \( U_B \), it is concluded that, the

\[ \Delta V_{th} \]

where \( V_{th} \) is the threshold voltage of the p-n junction.

### IV. Conclusion

A novel insulated-gate photoconductive semiconductor switch (IGPCSS) structure is presented. It attains a monolithic integration of a PCSS and MISFET cells thereby yielding less leakage current and higher photoelectric-conversion efficiency compared to a relevant traditional PCSS. Through the simulation analyses of the static and the dynamic characteristics, the GaN-based IGPCSS design is validated.

### References