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A comparative investigation on sub-micrometer InN and GaN Gunn diodes working at terahertz frequency

Lin'an Yang, Shuang Long, Xin Guo, and Yue Hao
State Key Discipline Laboratory of Wide Band Gap Semiconductor Technology, School of Microelectronics, Xidian University, Xi'an 710071, China

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We report on a simulation for wurtzite-InN and GaN Gunn diodes with notch-doping and uniform-doping structural transit regions. Results show that 0.3–1.0 μm Gunn diodes with a diode area of 500 μm² can generate fundamental frequencies of around 0.2–0.8 THz and rf currents of several hundred mA. InN diodes exhibit more stable oscillations, whereas GaN diodes generate higher oscillation frequencies at both dipole-domain mode and accumulation-domain mode due to different negative differential resistance (NDR) characteristics of high-field transport. The sharp NDR region of InN makes it more suitable for short transit region Gunn diode. Higher Ipeak/Iavg and lower bias voltage in InN Gunn diode imply its conversion efficiency significantly higher than GaN diode. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4721667]

I. INTRODUCTION

Indium nitride (InN) has exhibited huge potentials in optoelectronics. Ternary alloys of InN with gallium nitride (GaN) and aluminum nitride (AlN) make it possible to extend the emission of light-emission diodes or laser diodes from ultraviolet to infrared wavelength. InAIN and InGaN also find applications in microwave power devices such as GaN high electron mobility transistors. However, the use of bulk InN material in power electronics has not attracted much interest so far because InN exhibits the narrowest bandgap among nitride semiconductors. Recent reports on high-field transport of bulk InN material demonstrate that InN possesses more evident velocity overshoot in its velocity-field characteristic compared with GaN and AlN, which means it has much more negative differential resistance (NDR) characteristic. Application of this property in transferred-electron device such as Gunn diode can achieve more stable oscillation signals in millimeter wave and terahertz regimes. There have been some theoretical investigations on InN Gunn diodes recently, showing attractive output performance of long transit region (>1 μm) device. In fact, InN is more suitable for short Gunn diode capable of generating higher frequency and conversion efficiency because distinguished NDR characteristic of InN assures the stability of oscillation in shorter transit region of Gunn diode. In this paper, we employ the ATLAS simulator of SILVACO (Ref. 12) to comparatively investigate properties of wurtzite InN- and GaN-based Gunn diodes. Submicrometer transit regions with different doping structures are designed in order to keep Gunn diodes working at terahertz frequency. Theoretical explanations of simulation results are also given with an emphasis on the influence of different NDR characteristics between InN and GaN.

II. MODELING OF HIGH-FIELD TRANSPORT

We have proposed an improved negative-differential-mobility (NDM) model for GaN and AlGaN which can be extended to InN and InGaN. In fact, this kind of model is a drift-diffusion transport based semi-empirical model where fitting parameters are determined by Monte Carlo (MC) simulation data or experimental data. In this paper, we use same mobility model to characterize the high-field transport of wurtzite InN, and fitting parameters of the model are extracted from up-to-date MC simulation data, although there have been other MC data for bulk InN. Table I gives the extracted fitting parameters for low-field and high-field mobility models of InN at 300–500 K, which can be directly invoked by ATLAS simulator. The calculated electron drift velocity versus electric field of bulk InN and GaN materials under the doping concentration of ~10¹⁷ cm⁻³ are plotted in Fig. 1, where the lattice temperature ranges from 300 to 500 K. The MC data for InN given in the figure are cited from Ref. 11, showing excellent agreement with our model. It is observed that InN exhibits more evident and early generated NDR characteristic than GaN, such as InN presents higher peak velocity (vpeak ≈ 4.5 × 10⁷ cm/s), lower saturation drift velocity (v₅₀ ≈ 1.2 × 10⁶ cm/s), and lower threshold electric field (E₀ ≈ 36 KV/cm) at room temperature, whereas those of GaN are vpeak ≈ 2.9 × 10⁷ cm/s, v₅₀ ≈ 1.9 × 10⁷ cm/s, and E₀ ≈ 220 KV/cm. Thus, the negative mobility μ(−) of InN is around 10 times larger than GaN. According to the Kroemer’s criterion for Gunn diode generating stable Gunn domain in the transit region, i.e., N × L > 3εₑ₀ρₑ₀μₑ₀[μ(−)], where N is the doping concentration and L is the length and vₑ₀ is the domain velocity (some articles usually use vpeak instead of vₑ₀), it is easier for InN to form Gunn domain even if the transit region is very short because of higher μ(−). Also shown in Fig. 1 are two nonlinear trace-lines between vpeak and v₅₀ of InN and GaN velocity-field curves that are used to analyze the Gunn oscillation characteristics (see Sec. IV). In the simulation, we also need to revise some material parameters of InN such as energy bandgap (Eₐ = 0.75 eV), Γ-valley electron effective mass (mₑ = 0.045 m₀), electron affinity, impact ionization coefficient, etc., cited from recent publications.
first obtain a direct current $I-V$ characteristic of Gunn diode by using a bias voltage scan to determine appropriate bias voltage and then carry out an instantaneous simulation at the chosen bias to achieve the radio frequency (rf) current signal through the diode.

In this paper, we investigate two types of Gunn diodes that include one with an $n^+\!-\!n\!-\!n^-$ and the other with an $n^+\!-\!n\!-\!n\!-\!n^-$ structures, where the use of notch-doping ($n^-$) region aims at creating an electric-field perturbation thereby promoting a formation of stable dipole-domain of electrons in the transit region. To generate terahertz frequency for both structural diodes, we propose the transit region of $0.3\!-\!1.0 \mu m$ in length sandwiched between $0.5\!-\!\mu m$ long anode and cathode contact regions. The notch-doping region adjacent to the cathode is included in the transit region, where it is fixed at $0.2 \mu m$ when total length of transit region is larger than $0.5 \mu m$, and is gradually shortened to $0.1 \mu m$ when total length is lower than $0.5 \mu m$, in order to keep a reasonable ratio of transit/notch region length. For comparison, we propose same structural parameters for InN and GaN Gunn diodes such as the transit region, the notch region, and the contact region are doped at $1.5 \times 10^{17} \text{cm}^{-3}$, $5.0 \times 10^{16} \text{cm}^{-3}$, and $2.0 \times 10^{16} \text{cm}^{-3}$, respectively. The specific contact resistivity of diode electrode is set as $5 \times 10^{-6} \Omega \cdot \text{cm}^2$ to fit the process reality. Because ATLAS is a 2-D simulator, we set the width of diode as $50 \mu m$ that is far larger than the length, so it is assumed as 1-D simulation. We put an emphasis on the lattice temperatures of $350\!-\!400 \text{K}$ in simulation because this temperature range fits the working reality. Actually, the temperature consideration of this kind is in a view of steady state in order to reduce the calculation consumption. Thus, the self-heating effect of transient state is not included in the simulation.

Because the transit region length of Gunn diode varies between $0.3$ and $1.0 \mu m$, we need to adjust the bias voltage at an optimal position according to $I-V$ scan characteristic. It is in a range of $7\!-\!10 \text{V}$ for $n^+\!-\!n\!-\!n^-$ and $9\!-\!12 \text{V}$ for $n^+\!-\!n\!-\!n\!-\!n^-$ uniform-doping InN Gunn diodes; a range of $20\!-\!35 \text{V}$ for $n^+\!-\!n\!-\!n\!-\!n^-$ uniform-doping GaN Gunn diodes, respectively, to assure the diode working at the deep NDR region. Then, we create an instantaneous simulation where the time-step is set as $25 \text{fs}$ to assure it far shorter than the energy relaxation time, and obtain rf current waveforms through Gunn diodes, from which the fundamental frequency $f_{osc1}$, the fundamental current component $I_{av}$ and the average current component $I_{av}$ are extracted by using FFT algorithm.

The use of $I_{av}$ and $I_{av}$ as well as $I_{osc1}/I_{av}$ aims at characterizing a maximal rf output capability of Gunn diode, which is more reasonable than calculating rf power density and conversion efficiency since we do not specify an external RLC circuit in this paper. Simultaneously, the distributions of electron concentration and electric-field in the transit region of Gunn diode are extracted to ascertain the oscillation mode.

### III. SIMULATION APPROACH AND DEVICE STRUCTURES

To improve the calculation efficiency of ATLAS simulator, we employ a self-excitation oscillation approach to simulate the performance of Gunn diode without connecting to a RLC resonant circuit, which is due to that ATLAS simulator usually regards external circuit as part of device thus significantly increases the calculation consumptions. In this case, the Gunn diode can only generate and sustain the stable oscillation at a narrow frequency range, different from that the Gunn diode mounted to an external resonant circuit has a tunable frequency-band. It means this simulation approach can reveal maximal output capability of a Gunn diode at an optimal oscillation frequency, so it is regarded as a device-fabrication-oriented simulation approach. To generate a stable NDR oscillation, the key issue is that the bias voltage across Gunn diode should be carefully adjusted to assure the Gunn diode working at appropriate position of deep NDR region, usually, forming an inner electric field of around two times higher than the threshold field. In the simulation, we

![Electron-drift-velocity–electric-field dependences of wurtzite InN and GaN bulk materials under the doping concentration of $\sim 10^{17} \text{cm}^{-3}$ and the temperatures of 300–500 K, where Monte Carlo data are cited from Ref. 11. The two nonlinear trace-lines represent a variation of domain drift velocity for InN and GaN Gunn diodes at 300 K, respectively, according to the equal-areas rule of Gunn diode.](image)

**TABLE I.** Fitting parameters for InN mobility model.

<table>
<thead>
<tr>
<th>High field $v_{sat} (\text{cm/s})$</th>
<th>$E_C (\text{K}/\text{cm})$</th>
<th>$a$</th>
<th>$n_1$</th>
<th>$n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K $1.26 \times 10^7$</td>
<td>36.70</td>
<td>4.665</td>
<td>3.306</td>
<td>0.9602</td>
</tr>
<tr>
<td>350 K $1.13 \times 10^7$</td>
<td>37.93</td>
<td>3.543</td>
<td>3.129</td>
<td>0.9375</td>
</tr>
<tr>
<td>400 K $1.01 \times 10^7$</td>
<td>39.79</td>
<td>2.679</td>
<td>2.983</td>
<td>0.9328</td>
</tr>
<tr>
<td>450 K $0.91 \times 10^7$</td>
<td>42.78</td>
<td>2.093</td>
<td>2.903</td>
<td>0.9647</td>
</tr>
<tr>
<td>500 K $0.86 \times 10^7$</td>
<td>47.32</td>
<td>1.835</td>
<td>2.931</td>
<td>1.054</td>
</tr>
</tbody>
</table>

**IV. RESULTS AND DISCUSSIONS**

For each length of transit region, we supply three bias voltages within the optimal range, e.g., $7$, $7.5$, $8 \text{ V}$ with $0.5 \text{ V}$. 
interval for InN diode and 31, 32, 33 V with 1 V interval for GaN diode, in order to reveal the dependence of oscillation frequency on bias voltage. After a 140 ps instantaneous simulation, the extracted $f_{osc1}$ versus transit region length of InN and GaN Gunn diodes are shown in Fig. 2, where (a) gives those of notch-doping structural and (b) gives those of uniform-doping structural Gunn diodes at temperatures of 350 K and 400 K, respectively. Fig. 3 demonstrates two typical electric-field distributions in the transit regions of notch-doping and uniform-doping Gunn diodes, respectively, indicating the notch-doping Gunn diodes generate oscillations at a dipole-domain mode, whereas the uniform-doping Gunn diodes generate oscillations at an accumulation-domain mode, regardless they are based on InN or GaN. In recent years, numerous articles on micrometer GaN Gunn diodes have demonstrated that the Gunn diode with a uniform-doping transit region could generate the oscillation at an accumulation-domain mode, whereas the diode with an un-uniformly doped transit region could generate the oscillation at a dipole-domain mode, because the notch-doping layer acts as an electron launcher therefore reduces the dead zone length and promotes the formation and propagation of dipole-domain (see Ref. 17 and references therein). In this simulation, both InN and GaN Gunn diodes manifest similar results, even if the transit region shrinks into submicron range. Note that the oscillation mode of Gunn diode can be affected by the circuit parameters when the Gunn diode is mounted to external resonant circuit. It is also found in Fig. 2 that $f_{osc1}$ decreases with rising bias voltage and rising temperature which consists with previous reports. From the divergence of simulation data at each point of length, we can observe that the variation of frequency with bias and temperature is smaller at the dipole-domain mode than the accumulation-domain mode, particularly for longer transit region. It means that the oscillation at dipole-domain mode is more stable than that at accumulation-domain mode for both GaN and InN Gunn diodes. Furthermore, InN is more suitable for short Gunn diode to achieve higher frequency compared with GaN. As the simulation showing, it is difficult to trigger the self-excitation oscillation for GaN diode under the doping concentration of $1.5 \times 10^{17} \text{cm}^{-3}$ when $L$ is down to 0.5 $\mu$m; however, InN diode can work even $L$ is down to 0.3 $\mu$m due to that InN Gunn diode has lower $N \times L$ limit. For the GaN Gunn diode with shorter transit region, we have to increase the doping concentration, otherwise, the oscillation changes to more and more unstable.

It is interesting that $f_{osc1}$ of InN Gunn diode is lower than that of GaN Gunn diode at both dipole-domain and accumulation-domain modes under the same device structure, as is shown in Fig. 2. It is known that the oscillation frequency of a Gunn diode is proportional to the domain drift velocity $v_{dom}$ which corresponds to the peak domain field $E_{dom}$ and $v_{dom}$ is inversely proportional to $E_{dom}$ at an NDR region. According to the equal-areas rule of Gunn diode theory, we have plotted the nonlinear trace-line characterizing a variation of $v_{dom}$ with electric field for InN and GaN, respectively, as is shown in Fig. 1. Two trace-lines manifest different dependence on electric field since $v_{dom}$ closely depends on $v_{peak}$ and $v_{sat}$. At the deep NDR region where the optimized bias locates, it is found that $v_{dom}$ of InN is slightly lower than that of GaN due to InN exhibits lower $v_{sat}$ than...
GaN, which pulls down $v_{dom}$ in spite of $v_{peak}$ is higher for InN. To assure the propagation of electron domain as is shown in Fig. 3, the InN Gunn diode working at deep NDR region has to generate high peak domain field $E_{dom}$ therefore causes a decrease in average $v_{dom}$ consequently a decrease in oscillation frequency. As validation, we employ MC data of high-field transport in Ref. 7 to fit the mobility model of InN. The fitting parameters are certainly different from those in Table I because the high-field transport proposes higher $v_{peak}$ of around $6.0 \times 10^7$ cm/s and lower $E_{th}$ of around 22.5 KV/cm, as well as a $v_{sat}$ of lower than $1.5 \times 10^7$ cm/s. It is not found an evident increase in oscillation frequency except a decrease in optimal bias voltages (the simulation results are not shown in this paper). Thus, we assume that it is the lower $v_{sat}$ of InN that causes a lower oscillation frequency. Theoretically, reducing the doping concentration of transit region is an effective approach to increase oscillation frequency because it can elevate the outside-domain-field $E_r$ and reduce $E_{dom}$ consequently raises $v_{dom}$. Fortunately, a lower $N \times L$ limit for InN Gunn diode makes it possible to significantly reduce the doping concentration without shortening the transit region. We propose different doping concentrations between $5 \times 10^{16}$ cm$^{-3}$ for 1-um InN Gunn diode with a notch-doping and a uniform-doping structure, respectively. The results are given in Fig. 4, showing a rising $f_{osc1}$ with respect to a decreasing concentration. The tendency of this kind is more evident for shorter InN Gunn diode in our simulation that is not presented in this paper.

We also extract $I_{rf}$ and $I_{av}$ from rf current waveforms of InN and GaN Gunn diodes with notch-doping and uniform-doping structural transit regions at temperatures of 350 K and 400 K in Figs. 5(a) and 5(b), respectively. Corresponding to each length of Gunn diodes, the simulation results demonstrate that $I_{rf}$ increases with bias voltage but decreases with temperature, which has been discussed in previous articles on GaN Gunn diodes. Both InN and GaN Gunn diodes can output $I_{rf}$ of several hundred mA (it is estimated by using the diode area of 500 $\mu$m$^2$), where maximal $I_{rf}$ are obtained from InN uniform-doping Gunn diodes. $I_{av}$ is significantly higher for uniform-doping than notch-doping Gunn diodes because it requires higher outside-domain-field $E_r$ to trigger the oscillation in the transit region with a uniform electric-field compared with a perturbative electric-field. GaN diodes show higher $I_{av}$.
than InN diodes under the same structure; therefore, InN diodes exhibit higher $I_{sat}/I_{av}$ than GaN diodes both at dipole-domain mode and at accumulation-mode, as shown in Fig. 6. Considering the bias voltage of GaN diode is 4–5 times larger than InN diode at the deep NDR region, one can predict that the dc-to-rf conversion efficiency of InN diode is significantly higher than GaN diode.\textsuperscript{10} The dependence of $I_{sat}$ and $I_{av}$ upon the doping concentration is also investigated with the simulation results given in Fig. 7, showing that both $I_{sat}$ and $I_{av}$ evidently decrease with doping concentration of InN Gunn diode. It is due to that a decrease in doping concentration causes both a decrease in $E_{don}$ and an increase in $E_{c}$; therefore, the electron domain possesses lower output power. An early generated NDR region with a large ratio of $v_{peak}/v_{sat}$ for InN high-field transport makes the output performance of InN Gunn diode more sensitive to the doping-concentration than GaN Gunn diode. With this aspect, it may not be suggested to excessively increase the doping concentration of InN Gunn diode to pursue high output power because of narrower bandgap for InN, although it is yet difficult to obtain low-doping InN materials nowadays.

\section*{V. CONCLUSION}

We have comparatively investigated wurtzite-InN and GaN Gunn diodes with notch-doping and uniform-doping structural transit regions. Simulation results show that 0.3–1.0 $\mu m$ Gunn diodes with an assumed diode area of 500 $\mu m^2$ can generate the fundamental frequency from around 0.2 THz to nearly 0.8 THz and the rf current of several hundred mA. InN diodes exhibit more stable NDR oscillations, whereas GaN diodes generate higher oscillation frequencies at both dipole-domain mode and accumulation-domain mode, all of which is due to different NDR characteristics of high-field transport between InN and GaN materials, where InN exhibits higher $v_{peak}$ and GaN has higher $v_{sat}$. The early generated and sharp NDR region with higher ratio of $v_{peak}/v_{sat}$ for InN makes it more suitable for short Gunn diode, and the output performance is more sensitive to the doping concentration of transit region comparing to GaN. Higher $I_{sat}/I_{av}$ and lower bias voltage for InN Gunn diode in our simulation imply that the conversion efficiency of InN diode is significantly higher than GaN diode, which is helpful to the coming fabrication of Gunn diodes in respect of heat-sinking.

\section*{ACKNOWLEDGMENTS}

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\begin{thebibliography}{999}
\bibitem{8} S. Vitanov and V. Palankovski, \textit{Annu. J. Electron.} \textbf{4}, 18 (2010).
\bibitem{12} See \url{http://www.silvaco.com} for Atlas User’s Manual, Version 5.16.3.R.
\end{thebibliography}