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SIMULATION AND EXPERIMENTAL RESULTS ON GaN BASED ULTRA-SHORT PLANAR NEGATIVE DIFFERENTIAL CONDUCTIVITY DIODES FOR THz POWER GENERATION

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A GaN based negative differential conductivity diode utilizing transient ballistic transport effects is proposed and large-signal circuit simulations along with preliminary experimental results are presented. The diode is an n^+-n-n^+ structure and transport is described by an empirical velocity-field relation which is derived directly from femtosecond pulse-probe measurements available in literature and incorporated into the simulations through curve fitting. Efficient THz generation is predicted as a result of ~2.8 peak-to-valley ratio. Pulsed current-voltage characteristics were measured and N-type dependence was observed.

Keywords: Terahertz; Ballistic Transport; Negative Differential Conductivity; Negative Differential Resistance; Planar Diode; GaN Diode

1. Introduction

A number of novel approaches have been suggested to fill the THz gap, a frequency range that is difficult to cover neither with optical nor with electronic devices. Quantum cascade lasers [1] show promising results, producing mW of CW power; however room temperature operation still remains a major challenge. Terahertz emission from ultra-short gate FETs at room temperature has recently been detected in which plasma wave generation due to Dyakonov-Shur instability is responsible [2] and more theoretical and experimental work is on the way to optimize this phenomena. In this article however, we propose a different device approach. It relies on the strong transient ballistic transport properties of electrons drifting in an ultra-short GaN channel under the influence of strong bias fields. This leads to velocity reduction with increasing field and creates a strong negative differential conductivity (NDC) which is fast enought to generate THz radiation. We call this device the BEAN diode (Ballistic Electron Acceleration Negative differential condutivity). Electron transport for this device is described by an empirical velocity-field characteristic derived from the femtosecond pulse-probe experiments of Wraback et al. [3, 4] and is shown in Fig. 1 (solid triangles)

Using light pulses with photon energy just above the GaN bandgap, he was able to measure the electron accumulation layer drift velocity vs. time in a micron long GaN sample, biased at series of electric field strenghts. Most of these transient effects occured in the first ~250 nm drift region. Therefore, by selecting a 250 nm long channel, the average transit velocity can be determined at this and other bias field strengths. This yields the average drift velocity vs. electric field for such a channel as shown in Fig. 1. Intervalley transition time in GaN has been measured by Wu et al [5] and is reported to be comparable to their 0.17 ps pump time. Furthermore, close inspection of Wraback et al's velocity-time measurements at high fields indicates that the drift velocity drops rapidly within ~0.3 ps after the peak value of ~7×10^{7} cm/s has been reached. This value is made longer than its real value due to the 0.07 ps pulse and 0.1 ps probe times in his experiments. Therefore, his data roughly substantiates Wu et al.'s ~0.17 ps as the intervalley transition time. This time constant, together with the the acceleration time at the end of which the electron reaches at or above ~1 eV kinetic energy (enabling the electrons to transfer), determine the 3dB cut off frequency. This acceleration time can be estimated from the acceleration law $\hbar\dot{k} = qE$ as ~50 fs using the value of k as the boundary condition at which $E(k) \simeq 1\,eV$. Therefore, the 3 dB cut off condition f=1/τ, requires τ = 56 + 170 = 226 fs, which corresponds to a frequency of ~4.5 THz. There may be, in addition to electron transfer in Wraback et al's data, also a modest amount of phonon build up and even electron negative effective mass effect responsible in the velocity reduction observed. Thus, through the transient ballistic transport effects, it is possible to create NDC with a very fast time response.

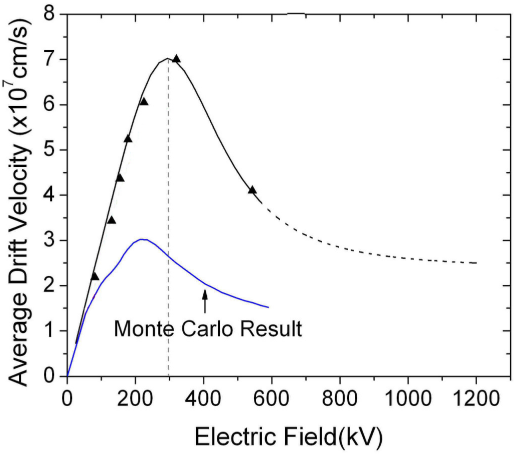


Fig. 1. Drift velocity versus electric field constructed from experimental measurements. Solid curve is a fit to the discrete experimental data. Also shown in continuous line is a typical Monte Carlo result to contrast the transient ballistic effects involved in transport over short distances.

2. Simulation Results

The diode is modeled as one-dimensional n^+-n-n^+ structure with a doping profile of 1×10^{20}, 1×10^{18} and 1×10^{20} cm^{-3}, respectively. Previously, other simulation results have been reported for long n+-n-n+ channels [6,7].

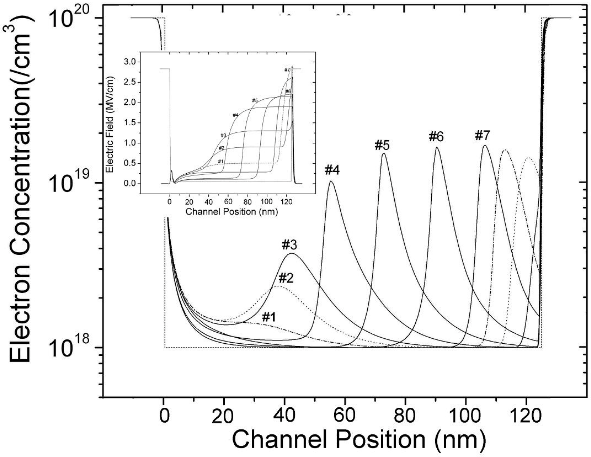
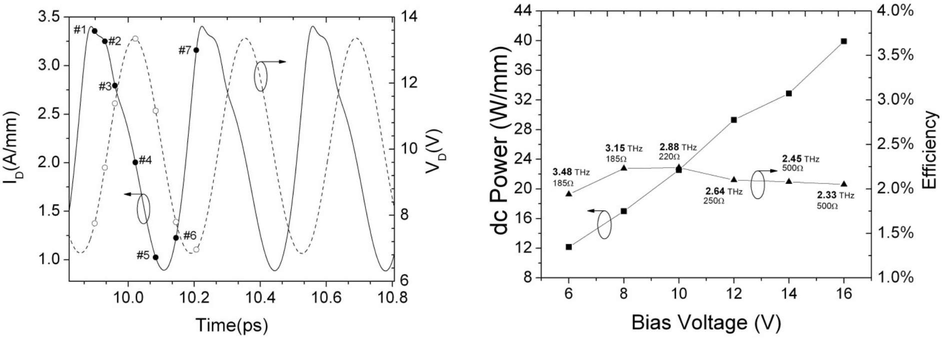


Fig. 2. Electron concentration vs. position at different instance of time (numbered labels) showing accumulation layers in transit towards the anode. Inset shows the accompanying spatial distribution of the electric field.

The n^+ layers are important for good ohmic contacts and also serve to provide electron concentration gradient for the nucleation of accumulation layers. The channel doping is chosen to meet the doping-length product criterion, *NL*, to allow space charge instabilities and also is crutial for the generation of a useful a.c. power level. Poisson and current continuity equations are solved within the framework of drift-diffusion approximation using physics-based device simulator "ATLAS" (Silvaco Inc.). Diffusion coefficient is calculated for each electric field value using the Einstein's relationship.

The applicability of the derived velocity-field characteristics at 1×10^{18} cm^{-3} doping level, (which was constructed from measurements performed in a 1×10^{15} cm^{-3} doped sample) is justified by the fact that the hot electrons, as is the case in these diodes under bias, are only minimally affected by the impurity scattering. This has been verified by Foutz et al. in GaN through Monte Carlo simulations [8]. Moreover, from a fabrication perspective, 1×10^{18} cm^{-3} is appropriate since typical molecular beam epitaxy (MBE) doping profiles are significantly more reproducible above ~5×10^{17} cm^{-3}.

To ensure accuracy, time steps have been chosen to be much less than the dielectric relaxation time, $\Delta t \ll \tau_\varepsilon$, and likewise, spatial mesh size much less than $v\tau_\varepsilon$ where v is the average velocity of the electrons [9]. The diode is assumed to be in parallel with a parallel RLC circuit where C represents the geometric capacitance of the diode (4.2 fF), R is the load resistor (220 Ω) and L is the inductor to create resonance (0.61 pH). The geometric capacitance is dominated by the fringing fields penetrating GaN due to ~10:1 ratio of its dielectric constant to air. The device is designed 50 µm wide with a channel thickness of 20 nm. When biased above the threshold voltage V_{TH}, accumulation layers nucleate and are periodically drawn from the n^+ layer at the cathode and propagate towards the anode where they are collected as shown in Fig. 2. This leads to current-voltage oscillations at the terminals of the diode at the transit time frequency.



(a) (b)

Fig. 3. (a) Current-Voltage waveforms as a function of time. (b) Efficiency and d.c. Power dissipation vs. bias voltage for a 125 nm device. Frequency and the optimum load resistors are also labeled.

This particular simulation was performed for 10 V bias. The output wave forms were Fourier analyzed and following performance parameters were calculated: 2.9 THz. fundamental frequency, 0.5 W/mm a.c. output power (~25 mW) at 2.22% conversion efficiency, 6.68 V peak-to-peak voltage swing amplitude, 1.96 A/mm peak-to-peak current swing amplitude. The current-voltage oscillations at the terminals are shown in Fig. 3a. In Fig. 3b, bias dependency of the conversion efficiency is shown. For each bias point, load resistor and the parallel inductor has been tuned in order to maximize the efficiency.

3. Experimental results and discussion

In order to verify simulation results, a device with contact spacing of ~125 nm was produced. This device was fabricated on GaN bonded to a polycrystalline diamond substrate for thermal management. The GaN growth contained a 40 nm thick n-type epilayer doped at $1x10^{18}$ cm^{-3} and a 190 nm thick n^+ region doped at $1x10^{20}$ cm^{-3} in order to reduce ohmic contact resistance. Several devices were fabricated and exhibited negative differential conductivity (NDC) characteristics. The fabrication required removal of the n+ region to properly form the channel of the device. During fabrication a thin n+ region, approximately 10 angstroms thick, remained after the etch that caused an undesirable shunt conductance.

Shown in Fig. 4 is the measured result of the device under 200 ns pulsed I-V measurements, also shown is an estimated correction for the shunt conductance. A large peak to valley ratio is expressed in this device and is on the order of the expected result based upon Wraback's data [3, 4] shown in Fig. 1. The approximate field strength of the peak velocity is at approximately 300 kV/cm, based upon the etch angle of the channel and assuming mild ohmic conductive losses. Due to the shunt conductance the devices failed shortly after measurement, but several devices displayed near identical characteristics though with slightly smaller peak to valley ratio's than is shown in Fig. 4. While these results are initial, we expect that reliable devices will be produced in the near future.

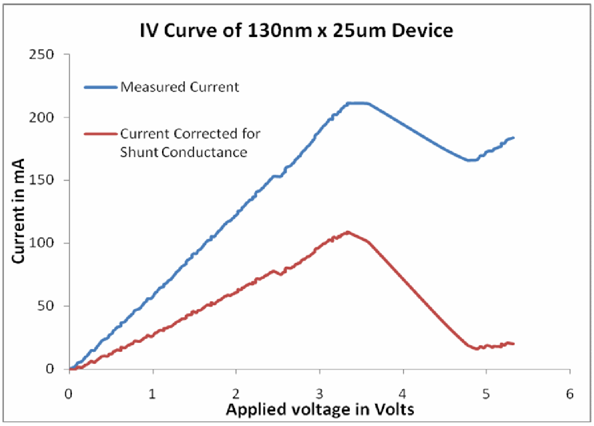


Fig. 4. The top plot indicated the measured results including an undesirable shunt conductance due to a thin n+ region that was not completely etched. The bottom plot is an estimated correction based upon a 10 angstrom thick n+ layer.

4. Conclusion

Large signal simulation results of GaN NDC diodes based on an empirical velocity-field relation is presented and efficiencies up to 2.3 % is shown to be possible utilizing the transient transport effects in ultra-short distances. To implement these devices, a fabrication technique has been developed and preliminary results of pulsed I-V measurement of a ~125 nm device have indicated N-type dependence.

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