GaN THz Electronics

Dimitris Pavlidis[1]

[1]The University of Michigan, Department of Electrical Engineering and Computer Science, Ann Arbor, MI 48109, USA; Technical University of Darmstadt, Department of High Frequency Electronics, Merckstrasse 25, D-64283 Darmstadt, Germany; Institute of Electronics, Microelectronics and Nanotechnology, 59652 Villeneuve d'Ascq Cedex, France; Phone: +1-734-647-1778; +49-6151-16 24 52, E-Mail: pavlidis@umich.edu

***Abstract* — The use of GaN in THz electronic applications is discussed. The devices addressed include Negative Differential Resistance (NDR), Superlattice diodes and Plasma Wave devices. Fundamental considerations of the transport properties are made to explore the high frequency potential of this material system. The use of new concepts for GaN THz electronics is also addressed.**

I. Introduction

High-frequency/high-speed electronic devices and circuits are often based on traditional III-V semiconductors such as GaAs. THz electronics rely strongly on III-V semiconductor devices based on GaAs and InP substrates in order to perform signal generation, amplification, mixing and multiplication. InP-based heterostructure MMICs have shown THz promise more than a decade ago [1] and recent developments have confirmed further the merits of this approach for signal generation and treatment at several hundred GHz. Other THz approaches include Si/SiGe Quantum Cascade Emitters (R. Kelsall et. al., U of Cambridge), Boron-doped silicon devices (J. Kolodzey et. al., U of Delaware) and InAsAlSb superlattices (S.J. Allen et. al., UCSB). Wide bandgap semiconductors such as III-V nitrides (Eg=3.4eV for GaN vs. 1.4eV for GaAs) offer an interesting alternative to traditional III-Vs due to the possibility of operation with a higher output power resulting from the increased critical field (E_{CR}=2MV/cm for GaN vs. 0.4MV/cm for GaAs), higher saturation velocity ($V_{SAT}=2\times10^7$cm/sec for GaN and 1×10^7cm/sec for GaAs), and better thermal conductivity (1.3W/cm for GaN and 0.5W/cm for GaAs). Thus not only high power but also high frequency, THz capability is expected from GaN-based semiconductors [2].

This paper addresses the use of GaN-based devices in THz electronics. The topics discussed include Negative Differential Resistance (NDR) and Superlattice diodes, Plasma-Wave devices and fundamental considerations of transport properties and device concepts with a potential for use in THz electronics.

II. Transport Properties In GaN Based Semiconductors

Before proceeding to more detailed discussions of GaN use in THz electronics, it is important to consider the basic transport properties of this material system and its suitability for high frequency and NDR applications.

Numerical simulations of the drift velocity vs. electric field dependence based on the ensemble Monte Carlo approach were performed by various groups and showed that GaN exhibits negative differential mobility. Various possibilities are suggested for the nature of the NDR effect, including the electron intervalley transfer and the inflection of the central valley. Although further confirmation is needed for the latter, Gunn domain instability is expected to be present according to the simulated velocity-field characteristics. Comparison of electron transit time of GaN and GaAs based on Monte Carlo simulations shows considerably reduced times for GaN due to the higher velocity of this material. This implies that GaN NDR devices should have higher operation frequencies than GaAs devices, since the operation frequency is directly proportional to the transit time. Moreover, consideration of scattering mechanisms present in GaN and their temperature dependence shows that NDR operation is expected to be limited more for higher doped diodes and higher temperature of operation.

An optically-detected time-of-flight technique with femtosecond resolution that monitors the change in the electroabsorption due to charge transport in a p-i-n diode was employed by Wraback et al. and showed how it may be used to determine the electron transit time and velocity-field characteristic in GaN at room temperature [3]. A measurement of the high field transient electron velocity overshoot was performed using a semi-transparent p-contact AlGaN/GaN heterojunction p-i-n diode. Further experiments employed an AlGaN/GaN diode rather than a ring p-contact to avoid current crowding and non-uniform fields and thus obtaining a more accurate picture of the effects taking place [4]. The latter demonstrated steady state and average velocities in

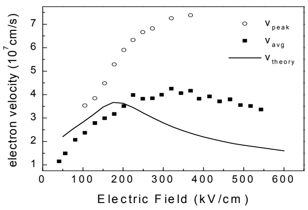

Fig. 1. Experimental and theoretical electron velocities as a function of field. Circles: peak transient velocity; squares: average velocity; line: full zone calculation of steady-state velocity in the c-direction [After2]

closer agreement with theoretical data. This study is very relevant to NDR effects in GaN since it provides further insight into its presence in this material. The experimentally determined electron velocity of Fig.1 was obtained from the transit time based on theoretical expectations. The steady-state velocity-field characteristic derived from an Monte Carlo EMC calculation including a full Brillouin zone band structure is shown in Fig. 1 for comparison with the measurements. The theoretical results are in qualitative agreement with the data.

A peak transient electron velocity of 7.25´10^7 cm/s within the first 200 fs after photoexcitation has been observed at a field of 320 kV/cm. At higher fields, the measurement of the peak velocity is limited by the 80 fs duration of the pulses, but the increase in transit time with increasing field suggests the onset of negative differential resistance.

The results obtained from such studies combined with investigations of transport along the a- and c-axis of GaN may have a dramatic effect on the design of THz electronic devices and NDR diodes. Based on them, lateral high frequency electronic devices such as HFETs could benefit by operating with transport in the c-direction, for which both the transient and steady-state electron velocity are higher. On the other hand, vertical devices such as avalanche photodiodes may improve with transport in the basal plane, for which intervalley transfer leading to impact ionization is more likely and the existence of a negative effective mass does not preclude diode breakdown. GaN NDR devices are for the above-mentioned reasons explored in both the c- and a-direction since traditional NDR by intervalley transfer may be possible in the a-direction while c-direction NDR operation may or may not be feasible by non-parabolicity effects depending on the energy of states available and the current associated with such a mechanism.

III. GaN Based Negative Differential Resistance (NDR) Diodes

Frequency-independent *v-F* characteristics can be used to describe electron transport in the presence of time-varying electric field as long as the frequency of operation f is much lower than the NDR relaxation frequency f_{NDR} defined by τ_{ER} (the energy-relaxation time) and τ_{ET} (the intervalley relaxation time). The energy-relaxation time of *0.15ps* calculated for *Wz* GaN is ten times smaller than the GaAs value of *1.5ps*. The intervalley-transfer relaxation time τ_{ET} was evaluated from the results of Monte Carlo studies of ballistic transport. By extrapolating reconstructed $\tau_{ET}(F)$ curves to the point of threshold field $F=F_{TH}$, electron intervalley transfer times τ_{ET} of *7.7ps* and *1.2ps* were found for GaAs and GaN, respectively. Based on the results of this straightforward analysis, the NDR relaxation frequency f_{NDR} of GaAs was found to be *~105GHz* in excellent agreement with experimental and theoretical results. The frequency capability of GaN-based NDR devices was found superior to that of GaAs Gunn diodes as indicated by the GaN NDR relaxation frequency f_{NDR} of *~700GHz* for case of intervalley-transfer-based NDR

Typical GaN NDR diodes designed to operate at ~100GHz are expected to have an n-type active layer with thickness L_A of 3 μm and doping N_A of $1\times10^{17}cm^{-3}$. The active layer will be sandwiched between anode and

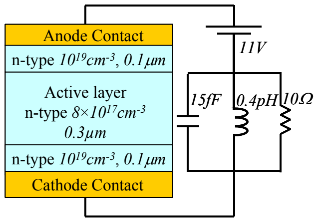

Fig. 2. GaN THz Oscillator Design

cathode layers and their corresponding ohmic contacts. Both contact layers could be 0.1µm-thick and doped at $1\times10^{19}cm^{-3}$. The diameter of the diode D can vary and a 50µm value is reasonable for mm-wave applications. A THz design of GaN NDR diode (see Fig.2) would employ
a thinner layer (L_A = 0.3µm) to reduce transit time, higher doping ($N_A=8\times10^{17}cm^{-3}$) to speed up dielectric relaxation and smaller diode size (R_D=10µm) to reduce parasitic capacitance. Fundamental operation of such a diode at THz frequencies (f_0~750GHz) appears to be possible with conversion efficiency of ~1%.

When compared with GaAs Gunn diodes, GaN NDR diodes showed a significant improvement in terms of output power density and frequency. These results are supported by similar conclusions drawn with the help of the microwave signal generator figure-of-merit
$Pf^2Z=F_B^2 v_{PEAK}^2/4$, which measures the maximum output power (P) delivered from an oscillator to a matched impedance (Z) at a frequency (f). Based on the considered material properties, Pf^2Z for GaN is 50 to 100 times that of GaAs, indicating a strong potential of GaN for microwave signal generation.

IV. Processing

The dislocations in GaN significantly limit the lateral mobility in GaN films, whereas the vertical mobility is hardly affected. Based on this consideration, NDR devices should be designed and fabricated as vertical structures. However, other considerations related to basal plane transport features may dictate a lateral GaN NDR diode design. The general technology used to fabricate the above structure mainly involves anisotropic etching of the material using a series of masks and can be accomplished in about 5 to 6 masks, which is relatively inexpensive compared to other device fabrication. Etching of GaN material can be done using a dry etching technique such as reactive ion etching (RIE) or inductively coupled plasma etching (ICP) or a wet etching technique such as photo-electrochemical etching (PEC).

The basic fabrication steps for the on wafer technology starts with the isolation etch in order to electrically separate each device on the wafer. The next step is the mesa etch, which defines the placement of the ohmic contacts. Following the mesa etch is the actual deposition of the metal for the anode and cathode ohmic contacts. Finally the transmission lines i.e. coplanar waveguide lines and airbridges are defined and electroplated for on wafer, high frequency testing.

V. GaN NDR Characterization

Fabricated GaN devices (with 10 µm radius and 0.5µm

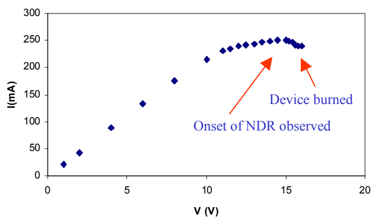

Fig. 4 I-V Characteristics of a GaN NDR device fabricated using the UofM process

thick active layer), were tested for DC characteristics and their current-voltage characteristics are shown in Fig. 4. The onset of NDR for this device was observed around 15V. The device burned and around 17V due to excessive power generation and poor heat dissipation. Further studies are pursued to investigate the diode characteristics under high pulse amplitude conditions to reduce the impact of thermal effects.

VI. Other NDR Device and Signal Generation Approaches

Various studies have shown that doped Esaki–Tsu superlattices exhibit negative differential conductance; the negative differential conductance is a consequence of Bragg reflection of miniband electrons, which are accelerated by an electric field [5]. Undoped superlattices can show photoexcited damped current oscillations. Recently, it was observed that a doped semiconductor superlattice with negative differential conductance showed self-sustained current oscillations. The oscillation frequency of 6 GHz was most likely caused by travelling charge density domains due to the negative differential conductance. A connection between Bragg reflection of band electrons and the occurrence of dipole domains has been discussed earlier. A millimeter wave oscillator based on self-sustained current oscillations in a superlattice was reported [5]. The superlattice was operated at room temperature. The superlattice structure was grown by molecular beam epitaxy on a n+ GaAs substrate, consisted of 100 periods of GaAs wells (3.45 nm thick) and AlAs barriers (0.96 nm thick) doped with silicon (10^{17} cm^{-3}). The superlattice was embedded between graded layers of gradual composition and doping level to avoid abrupt heterojunctions.

The obtained current–voltage characteristic showed regions of negative differential conductance, with current jumps, which give evidence for dynamical processes in the current flow. From the peak current (40 mA) and the mesa area we find a peak current density of 60 kA/cm^2 and a peak drift velocity of $4'10^6$ cm/s. This value is consistent with the propagation of electrons in the lowest miniband, for which we estimated, with a Kronig–Penney model, a width of 74 meV.

III-Nitrides are also a possible material system suitable for SL terahertz sources. GaN-based materials possess sufficient high frequency properties to deliver high power in the MMW and SMMW regions and are expected to enable compact, reliable, high power amplifier systems, capable of operating in harsh environments and temperatures with no need for cooling systems. The submillimeter sources may benefit from the advantages of the GaN material family. The traveling dipole domain oscillation frequency in group-III Nitride SL's has been calculated [6]. The estimations show that THz-range oscillations are possible using this material system. The properties of AlGaN/GaN superlattice related to the feasibility of a terahertz-range oscillator have also been addressed [7]. The distortion of the conduction band profile by the polarization-fields has been taken into account in this study and the conduction band offset between the pseudomorphic AlGaN barrier and the GaN quantum well, the first miniband width and energy dispersion have been calculated as functions of Al content in the barrier. Al content and superlattice period that favor high-frequency oscillations have been determined. A combination of the material properties suitable for high-temperature electronic and photonic devices and SL nonlinear effects could make the GaN material family a promising candidate for new types of applications such as terahertz-range electromagnetic generation.

Resonant tunneling diodes (RTD) based on GaN/AlGaN heterojunctions should in principle show high values of peak/valley ratio due to the large conduction band discontinuities between GaN and AlGaN. Moreover, such structures have been studied for use in quantum cascade lasers for near infrared emission. However, polarization fields can mask such benefits and make the design of RTD quite complicated. An atomistic point of view was applied to describe current flowing in GaN-based RTD and to investigate polarization issues [8]. The sp3d5s* tight-binding (TB) model and a transfer matrix approach were used to describe the proper scattering states of the RTD system. The TB model allowed to describe the whole Brillouin zone of the semiconductors and relax all the envelope function approximations usually made for treating tunneling problems in RTDs. It was observed that the effect of the polarization fields is to shift the transmission coefficient peaks while keeping a very high PVR.

Other device approaches possible to implement in GaN for THz applications are plasma wave devices. Plasma waves in a gated two-dimensional electron gas have a linear dispersion law, similar to that of sound waves. The transistor channel acts as a resonator cavity for plasma waves that can reach THz frequencies for a sufficiently short ~nanometer-sized field effect transistor. As was predicted in [9] when a current flows through a field effect transistor, the steady state can become unstable against the generation of plasma waves [Dyakonov–Shur instability] leading to the emission of an electromagnetic radiation at plasma wave frequencies. The emission is predicted to have threshold like behavior. It is expected to appear abruptly after the device current exceeds a certain threshold value for which the increment of the plasma wave amplitude exceeds losses related to electron collisions with impurities and/or lattice vibrations. The excitation of plasma waves in a field effect transistor channel can be also used for the detection of terahertz radiation. Recent reports demonstrated a resonant detection in GaAs-based high electron mobility transistors (HEMTs) and in gated double quantum well heterostructures. Terahertz emission of 0.4–1.0 THz by plasma generation was recently obtained by using an

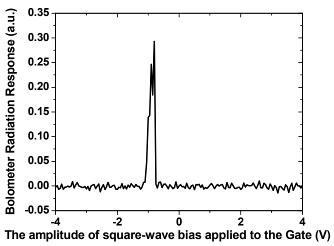

Fig. 3 Millimeter Wave Emission by GaN FETs {After 11]

InGaAs HEMT with a 60-nm-long gate [10]. The results can be interpreted assuming that the emission is caused by the current driven plasma instability leading to terahertz oscillations in the channel through Dyakonov–Shur instability. Millimeter-wave emission has also been reported from GaN-based FETs (see Fig3) [11]. Other approaches include semiconductor tunnel structures with negative differential conductance (NDC) that have originally been considered in AlGaAs/GaAs materials [12] but their concepts can also be applied to GaN designs. NDC appears due to tunneling through a Schottky barrier into a quantum well. This can be realized in structures similar to HEMTs with tunneling between the gate and two-dimensional channel.

VI. Conclusion

The basic properties of GaN materials are discussed and compared to other III-Vs such as GaAs. GaN-based devices are expected to present significant advantages in terns of power and frequency of operation. Various device concepts including NDR diodes, Plasma Waves and RTDs and devices with tunneling through the gate have been considered. Processing issues and experimental characterization is also reported.

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