ELECTRICAL TRANSPORT AND LOW FREQUENCY NOISE STUDIES ON GaN BASED BULK AND NANOSCALE DEVICES

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By

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Certificate

We are satisfied that the thesis entitled **"Electrical Transport and Low Frequency Noise Studies on GaN based Bulk and Nanoscale Devices"** submitted by **Mr. Ashutosh Kumar** is worthy of consideration for the award of the degree of Doctor of Philosophy and is a record of original and bonafide research work carried out by him under our supervision. The results contained in it have not been submitted in part or in full to any other university or institute for the award of any degree/diploma.

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Ashutosh Kumar

Abstract

Semiconductor devices based on GaN and its heterostructures have shown a tremendous potential for high-power, high-frequency and solid state lighting applications on bulk as well as nanoscale dimensions. In spite of a large number of efforts made towards the development of these devices, there are still issues which need to be resolved to utilize the full potential of GaN technology. Two such issues which affect the device properties are interface states and barrier inhomogeneities at metal/GaN interface. Therefore a detailed study related to their effect on electronic transport in GaN based devices is required. This thesis uses the electrical transport and low frequency noise characterizations to investigate electronic transport in GaN based bulk and nanoscale devices.

In GaN based devices for electronic applications, fabrication of a Schottky contact with high barrier height, near-unity ideality factor, low leakage current and good thermal stability is of utmost importance. In the present thesis, Ni/GaN Schottky barrier diodes have been fabricated and their electrical and low frequency noise characteristics are investigated as a function of measurement temperature, rapid thermal annealing temperature and applied bias. Temperature dependent electrical and low frequency noise measurements revealed the existence of barrier inhomogeneities at Ni/GaN interface which transforms the noise spectrum from Lorentzian towards $1/f$-type. After successful fabrication of these diodes, electrical and low frequency noise characteristics are studied as a function of rapid thermal annealing temperature. The diode subjected to rapid thermal annealing at 450°C for 60s showed decreased ideality factor, increased barrier height and reduced level of $1/f$ noise. The ideality factor decreased from 1.79 to 1.12 and barrier height increased from 0.94 to 1.13 eV with two orders lower $1/f$ noise in comparison to as-deposited diode. The independent contributions of interface traps and barrier inhomogeneities to the electronic transport are also investigated using temperature dependent current-voltage and bias dependent low frequency noise measurements. Our study suggests that low frequency noise characterization can be used as an independent technique for exploring electron transport at the metal/semiconductor interface in Schottky barrier diodes.

In addition to electronic and solid state lighting applications of GaN, large value of bulk spin polarization of Fe and long electron spin relaxation time in GaN make Fe/GaN ferromagnetic-semiconductor interface attractive for spintronic applications. Current-voltage and low frequency noise measurements as a function of temperature suggest the lesser inhomogeneous nature of Fe/GaN interface and presence of other current transport mechanisms in addition to thermionic emission at lower temperatures. As Schottky contact at ferromagnetic-semiconductor interfaces are desired in spintronics, rectifying behaviour of the Fe/GaN interface suggests that it could be potentially of use in spintronic applications.

Due to low density of states in graphene, its Fermi level is sensitive to graphene-metal and/or graphene-semiconductor interactions. As a result, electron transport in graphene based Schottky diodes is likely to different in comparison to conventional metal Schottky diodes. In present work, graphene/GaN Schottky diodes are fabricated by selective transfer of exfoliated graphene on GaN. The barrier height value obtained using thermionic emission theory is found to be higher than predicted value as per the Schottky–Mott model, which suggests that in such systems one can go beyond Schottky-Mott limit. The diodes exhibited enhanced thermionic emission and low $1/f$ noise in comparison to conventional Ni/GaN diodes. Our results indicate the potential of graphene as a Schottky contact in GaN based semiconductor devices.

In GaN based nanoscale devices, vertical alignment is beneficial for device processing. Large area fabrication of vertically standing GaN nanorods using Ni nanomasking and reactive-ion etching is demonstrated. The electrical behaviour of Schottky barrier diodes realized on vertically standing individual GaN NRs and array of NRs is investigated. The Schottky diodes on an individual nanorod show highest barrier height in comparison with large area diodes on nanorods array and epitaxial film which is in contrast with previously published work. The discrepancy between the electrical behaviour of nanoscale Schottky diodes and large area diodes is explained using cathodoluminescence measurements, surface potential analysis using Kelvin probe force microscopy and low frequency noise measurements. This is mainly due to limited role of barrier inhomogeneities at nanoscale dimension. These barrier inhomogeneities in large area diodes resulted in reduced barrier height whereas due to the limited role of barrier inhomogeneities in individual nanorod based Schottky diode, a higher barrier height is obtained.

The performance of any semiconductor device is affected by presence of charged surface states which produces local variations in surface potential. To study such variations and their impact on electrical behaviour, nanoscale analysis of AlGaN/GaN heterostructures using electrical scanning probe microscopy analysis is presented. Localized variations in surface contact potential difference is studied using Kelvin Probe Force Microscopy which gives a direct evidence of barrier inhomogeneities while localized variations in current-voltage characteristics are studied using conductive atomic force microscopy. The distribution of the barrier heights of the individual nanoscale Schottky contact obtained using conducting atomic force microscopy is consistent with the variation in surface potential obtained using Kelvin probe force microscopy analysis. As barrier inhomogeneities affect the electronic transport at metal-semiconductor interfaces, these findings may be useful for the further development of such interfaces in semiconductor devices.

Table of contents

List of figures

List of tables

Nomenclature

Symbols

A	Area of the Schottky diode
A^*	Richardson Coefficient
α	Hooge parameter
E_C	Conduction band edge
C	Capacitance of Schottky diode
C_R	Capacitance of depletion region
d	Thickness of interfacial layer between metal and semiconductor
D_{it}	Interface state density
$E00$	Tunnelling parameter
E_V	Valance band edge
E_F	Fermi level
E_g	Energy band gap
F	Occupation probability of interface states by electrons
f	Frequency
h	Planck's constant
I	Current
I_S	Saturation current
I_R	Reverse leakage current
k	Boltzmann constant
K	Kelvin
m_0	Free electron mass
m^*	Electron effective mass
η	Ideality factor of Schottky barrier diode
n_i	Intrinsic carrier concentration
N_D	Donor concentration
N_C	Effective density of states in the conduction band
N_T	Density of mono-energetic interface states
N_{SS}	Density of interface states widely distributed in energy
q	Electronic charge
Q_S	Space charge density in depletion region
Q_i	Interface charge density
Q_G	Total charge transfer due to graphene-semiconductor interaction

R_S	Series resistance
S_e	Capture cross section for electrons
S_V	Spectral power density of voltage fluctuations
S_I	Spectral power density of current fluctuations
S_V^{mono}	Spectral power density due to mono-energetic interface states
S_V^{Cont}	Spectral power density due to interface states distributed in energy
S_I/I^2	Normalized spectral power density of current fluctuaions
T	Temperature
V	Voltage
V_{bi}	Built-in-potential
V_{CPD}	Contact potential difference
ϵ_0	Permittivity of free space
ϵ_s	Permittivity of semiconductor
ϕ_B	Schottky barrier height predicted by Schottky-Mott model
ϕ_{bo}	Apparent barrier height obtained from I-V measurement
$\overline{\phi_{bo}}$	Mean barrier height obtained from C-V measurement
ϕ_m	Work function of the metal
ϕ_{bl}	Local barrier height of an individual patch of nanoscale dimensions
ϕ_g	Work function of the graphene
σ_S	Level of barrier inhomogeneties
ν_F	Fermi velocity in graphene
δ	Zero-bias depletion width
Δ_{tr}	Potential drop due to interfacial separation
Δ_g	Fermi level shift in graphene due to graphene-semiconductor interaction
$\Delta_c(d)$	Potential drop due to graphene-metal interaction
n_D	Defect density in graphene
I_G	Raman intensity of G peak in graphene
I_D	Raman intensity of D peak in graphene
L_D	Distance between two point defects in graphene
γ	Frequency exponent
$\Delta\sigma$	Magnitude of compressive stress relaxation
ϕ_{tip}	Work function of conductive tip
ϕ_{sample}	Work function of the sample
τ	Life time of a trap
χ	Electron affinity of semiconductor
ν_{th}	Thermal velocity of electrons
ϕ_0	Neutral level of interface states

Abbreviations

AFM	Atomic force microscopy
CAFM	Conductive atomic force microscopy
CL	Cathodoluminescence
C-V	Capacitance-voltage
CPD	Contact potential difference
DUT	Device-under-test
FE	Field emission
FESEM	Field emission scanning electron microscopy
FM/SC	Ferromagnetic-semiconductor
FWHM	Full width at half maximum
GR	Generation-recombination
HEMT	High electron mobility transistor
HFET	Heterostructure field effect transistor
HOPG	Highly oriented pyrolytic graphite
ICP	Inductively coupled plasma
I-V	Current-voltage
I-V-T	Temperature dependent current-voltage measurement
KPFM	Kelvin probe force microscopy
LED	Light emitting diode
LD	Laser diode
MOCVD	Metal organic chemical vapour deposition
MS	Metal-semiconductor
MOS	Metal-oxide-semiconductor
NR/NRs	Nanorod/Nanorods
NBE	Near band edge
PL	Photoluminescence
RIE	Reactive ion etching
RTA	Rapid thermal annealing
SBH	Schottky barrier height
SPM	Scanning probe microscopy
TE	Thermionic emission
TFE	Thermionic field emission
YL	Yellow luminescence
2DEG	Two dimensional electron gas