

Electron Transport Properties of Individual Gallium Nitride Nanowire Decorated with Gold Nanoparticles

Jency P Sundararajan and David N McIlroy

Abstract — Variations in the electron transport properties of individual n-type gallium nitride (n-GaN) nanowires decorated with gold (Au) nanoparticles as a function of nanowire diameter (~50nm – 400nm) have been studied. GaN nanowires were grown by vapor-liquid-solid (VLS) process and single nanowire devices were fabricated by photolithography techniques. Gold nanoparticle (~5nm-10nm) decoration was achieved by plasma enhanced chemical vapor deposition (PECVD). Two orders of magnitude drop of the current in gold decorated GaN nanowires compared to the bare GaN nanowires were observed. This effect is attributed to carrier depletion formed at the n-GaN nanowire/Au nanoparticle interface due to the formation of a metal-semiconductor Schottky junction. Variation in electrical conductivity of the nanowires with and without nanoparticles was highly dependent upon nanowire diameter for a constant nanowire length of 5 μ m. Bare GaN nanowire shows an exponential decrease in resistance (~ 450 K Ω to 1 K Ω) with increase in nanowire diameter (~ 50nm – 400nm). In case of Au-GaN nanowire, current-voltage measurements exhibited clear rectifying behavior, with the forward bias threshold voltage decreasing linearly with increasing nanowire diameter.

Index Terms – GaN nanowire, Au nanoparticles, Schottky barrier, nanowire conductivity.

I. INTRODUCTION

Electrically conducting materials at the nanoscale is currently one of the most intense research topics in nanotechnology as they can serve as building blocks for future nanodevices [1][2]. Carbon nanotubes (CNT), the most extensively studied one-dimensional nanomaterial, have been shown to exhibit unique electron transport properties as a function of their chirality. Many CNT based devices have been proposed and some have been realized [3][4][5][6]. However, semiconducting nanowires are preferred over CNTs as the electron transport properties of nanowires can be more readily controlled and modified with impurity doping. Gallium Nitride (GaN) is a direct band gap III-V semiconductor with band gap energy 3.39eV at room temperature. It is one of the most promising material for active electric and optoelectronic nanoscale devices in blue and near ultraviolet (UV) regions, laser diodes (LD's), light emitting diodes (LED's) etc [7][8]. Additional applications in the areas of spintronic nanosystems and in high-power/high-temperature electronics have also been

proposed. [9]. In this paper we discuss the variation in electron transport properties of individual n-type GaN nanowires decorated with Au nanoparticles as a function of nanowire diameter. Surface modification of GaN nanowire with Au nanoparticles gives rise to the formation of a Schottky contact, which in turn dramatically affects its transport properties.

II. EXPERIMENTAL PROCEDURE

The GaN nanowires were synthesized via the vapor-liquid-solid (VLS) process in a standard tubular furnace at atmospheric pressure [10]. A 50nm thick Nickel seed layer was deposited onto the silicon substrate which acted as the catalyst for nanowire growth. Molten gallium was coated on the inner side of a small half cylinder boat facing the substrate and was inserted into the center of a quartz tube in a tube furnace. Ammonia gas acted as the source of Nitrogen and GaN nanowires were grown at a temperature of 950°C. The as grown GaN nanowires are n-type. The nanowire mats were typically 10–20 μ m thick. A low magnification scanning electron microscope (SEM) image of a mat of GaN nanowires is shown in Fig. 1.

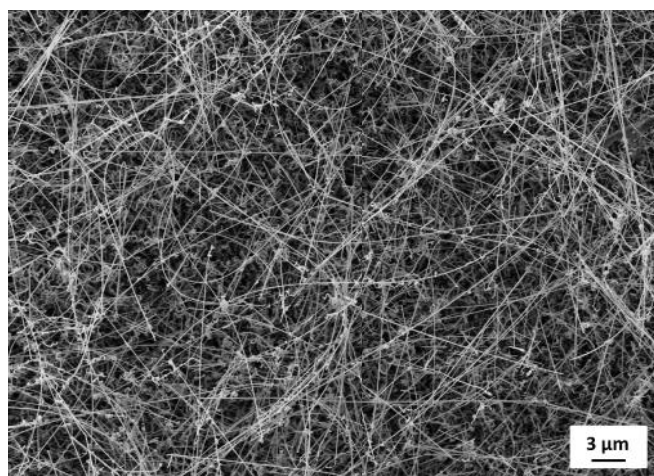


Fig. 1. Low magnification SEM image of a mat of GaN nanowires

In order to fabricate electrical contacts, GaN nanowires were released from the substrates by sonication in isopropyl alcohol for ~1 min and subsequently transferred to glass substrates. Patterns for electrical leads were generated using photo-lithography followed by successive deposition of Cr (50 nm) and Au (150 nm) by thermal evaporation. The fabricated devices were viewed with a field-emission scanning electron microscope (FESEM) to identify nanowires with good electrical contacts and to verify the Au

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nanoparticle decoration. The length and diameter of the identified were measured and marked for analysis. Fig. 2(a) is a FESEM image of a GaN nanowire between two electrodes. Upon completion of the device the I-V curves of the bare GaN nanowires were studied. Next, the electrically contacted GaN nanowires were decorated with Au nanoparticles with an average diameter of approximately 10nm by plasma enhanced chemical vapor deposition (PECVD)[11][12]. The PECVD system was operated at a frequency of 13.56 MHz and maintained at a base pressure of 35 mTorr. The substrate was heated to a temperature of 300°C to deposit gold nanoparticles. Prior to gold nanoparticle deposition the system was brought to a pressure of 325mTorr by introducing Ar as the carrier gas with the presence of Au precursor (98% pure dimethyl (acetylacetonate) gold (III), Strem Chemicals, Inc.). Fig. 2(b). is the transmission electron microscope (TEM) image of a GaN nanowire decorated with Au nanoparticles.

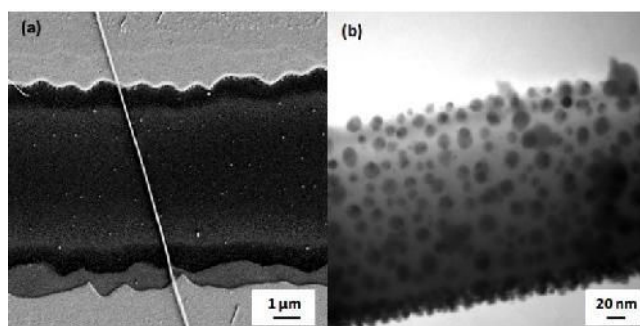


Fig. 2. (a) SEM image of an electrically contacted individual GaN nanowire and (b) TEM image of a GaN nanowire decorated with Au nanoparticles

A schematic of single nanowire device decorated with Au nanoparticles is presented in Fig. 3. The device is a standard two-terminal design with a constant distance of 5 μm between the electrodes.

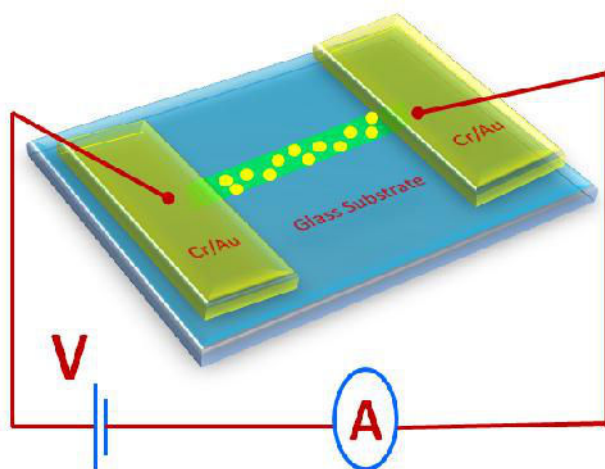


Fig. 3. Schematic of individual GaN nanowire device decorated with Au nanoparticles.

Electrical contacts to suitable pads were achieved with micromanipulator tungsten microprobes. The current-voltage measurements were conducted at atmospheric pressure and room temperature and were acquired using a Keithley-2400 source meter over the range of ± 2 V.

III. RESULTS AND DISCUSSION

Fig. 4. displays the current-voltage characteristics of a bare and Au decorated GaN nanowire with diameter 300nm. Ohmic behavior was observed for the bare GaN nanowire, whereas Au-GaN nanowire exhibits rectifying behavior with a turn-on voltage of 0.04V -0.13V in the forward bias region. The observed drop in electrical conductivity of Au nanoparticle decorated single nanowire is consistent with previous reported for mats of Au-GaN nanowires [13]. This drop is due to carrier depletion formed in the semiconducting GaN nanowire beneath the Au nanoparticles.

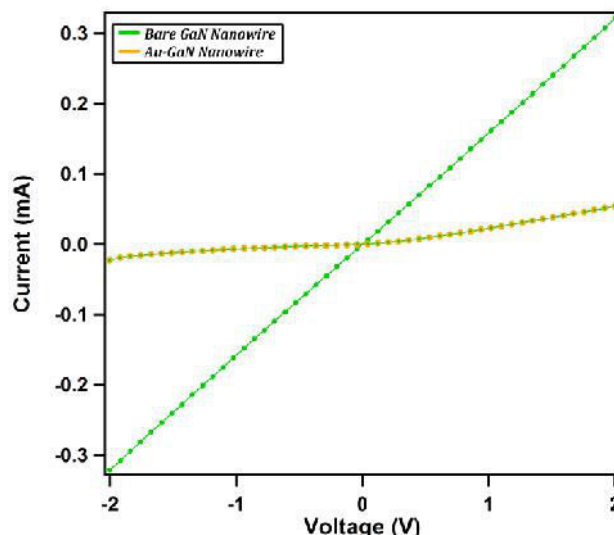


Fig. 4. Comparison of the current-voltage characteristics of an individual GaN nanowire of diameter 300nm decorated with and without Au nanoparticles

Current-voltage characteristics of bare GaN nanowire as a function of nanowire diameter are presented in Fig. 5. We observed a linear behavior irrespective of the diameter of the nanowire. The resistance was found to decrease exponentially (~ 450 K Ω to 1 K Ω) with increase in nanowire diameter (~ 50 nm – 400nm) as displayed in Fig. 6. The drop in resistance with increasing nanowire diameter is to be expected. Fig.7. summarizes the current-voltage characteristics of Au-GaN nanowire as a function of diameter. Compared to the bare GaN nanowire, we observe a factor of two drop in the conductivity of Au-GaN nanowires relative to bare GaN nanowires. This is due to the formation of a depletion layer at the interface between the Au nanoparticle and the GaN nanowire. The depletion width is effectively constant for a given nanoparticle diameter and distribution. Consequently, the depletion layer has less of an

effect on the conductivity of larger diameter nanowires.

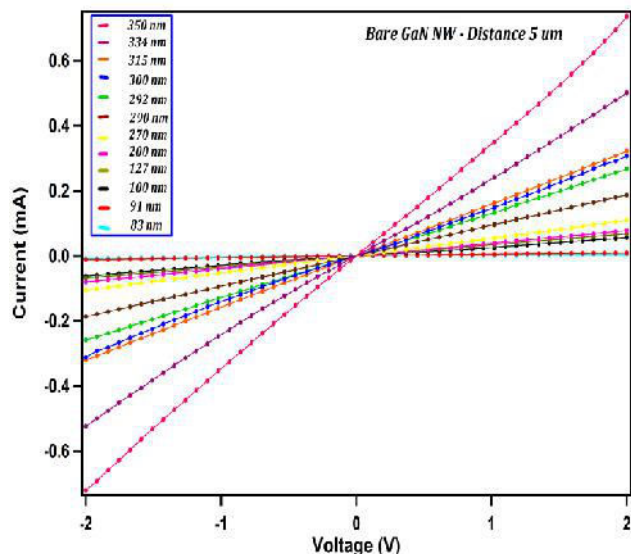


Fig. 5. Current-voltage characteristics of bare GaN nanowire as a function of diameter (65nm – 375nm) at a constant distance of 5 μ m between the electrodes.

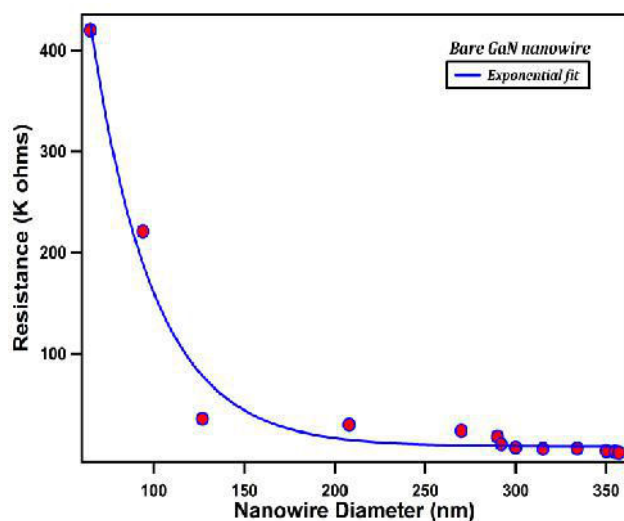


Fig. 6. Resistance vs nanowire diameter graph of bare GaN nanowire.

Interestingly, the IV curve is no longer Ohmic, i.e. nonlinear. This can be explained by the formation of localized Schottky junctions on the surface of nanowire due to Au nanoparticles induced surface band bending. Fig. 8. displays the exponential drop in resistance observed in Au-GaN nanowire at a given voltage of 2 Volts. Threshold voltage dependence in Au-GaN nanowire with respect to nanowire diameter is shown in Fig. 9. As the diameter increases, the threshold voltage decreases linearly. Once again, the current increases with increasing nanowire diameter. The mechanisms of the behavior of GaN nanowire with and without Au nanoparticles can be well understood by the model based on energy band theory, as proposed in Fig. 10. In case of a bare GaN nanowire (Fig. 10(a).) the depletion is due to Fermi-level pinning in n-type semiconductor giving rise to low conductance near the surface of the nanowire. This is highly dependent upon the

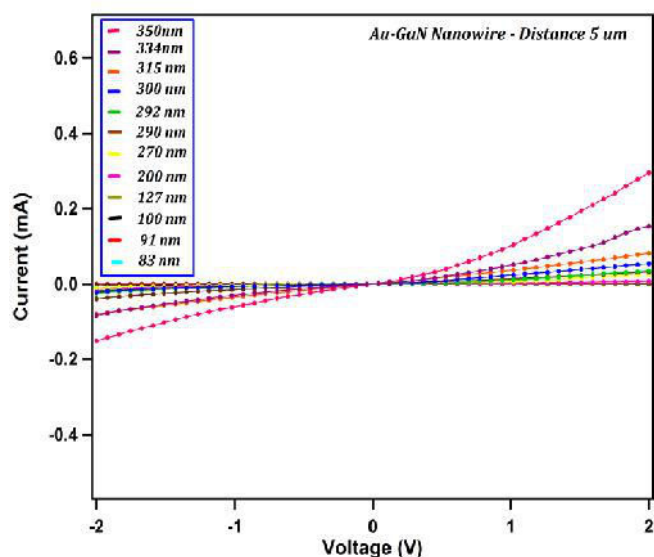


Fig. 7. Current-voltage characteristics of Au-GaN nanowire as a function of diameter (83nm – 350nm) at a constant distance of 5 μ m between the electrodes.

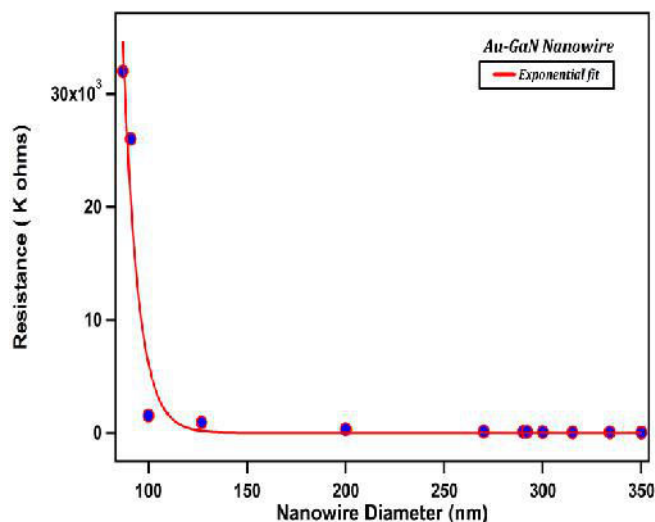


Fig. 8. Resistance vs nanowire diameter graph of Au-GaN nanowire at a given voltage of 2 volts.

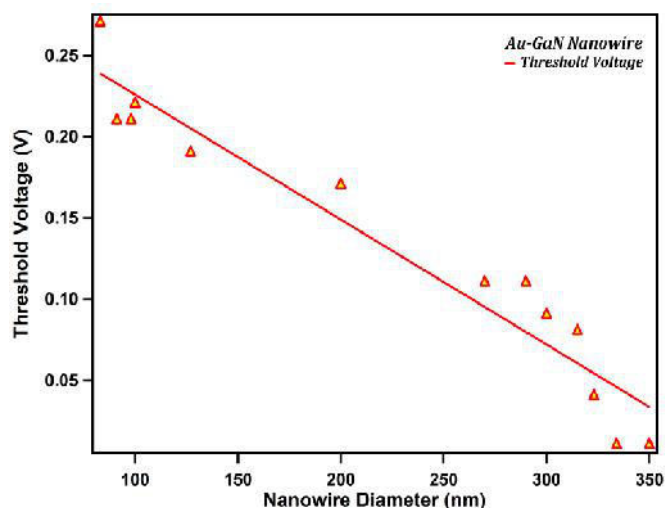


Fig. 9. Threshold voltage vs nanowire diameter of Au-GaN nanowire.

diameter of the nanowire. But for a Au-GaN nanowire (Fig. 10(b)), when the n-type GaN gets in contact with gold nanoparticles, the energy band of n-GaN is bent to align its Fermi level to that of the metal and the space charge region increases. The high work function of Au (5.1 eV) forms a localized Schottky barrier which increases the height and width of the space charge layer.

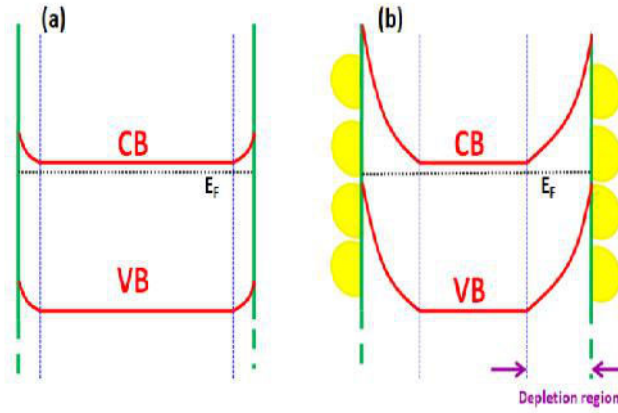


Fig. 10. Schematic of the energy band diagram near the surface of (a) bare GaN Nanowire and (b) Au-GaN nanowire in dark. CB and VB are the conduction band and valence band respectively.

Hence we can say that the large depletion formed inside GaN nanowire due to Au nanoparticles is the barrier for electron flow, which causes the drop in conductivity. As the GaN is n-type, a negative potential will increase the width of the depletion and restrict current flow. However, as the diameter of the nanowire increases ($> 100\text{nm}$), the effect of Au nanoparticle induced band bending decreases with nanowire diameter. Consequently, the nonlinear behavior becomes insignificant, such that at a nanowire diameter of $\sim 400\text{ nm}$ the effect of the Au nanoparticles is negligible. Hence the nanowire diameter is critical and plays a vital role depending upon the selectivity and sensitivity of the device.

IV. CONCLUSION

We have fabricated single nanowire devices using GaN nanowire with and without Au nanoparticles in order to study their electron transport properties as a function of nanowire diameter. Bare nanowires exhibited an exponential drop in resistance ($450\text{K}\Omega - 1\text{K}\Omega$) as a function of diameter. A drop in conductivity in Au-GaN nanowires relative to bare GaN nanowires was observed, and is also highly dependent on its diameter. Nonlinear behavior in Au-GaN nanowire was more prominent when the diameter of the nanowires is less than 100 nm . The threshold voltage ($0.27\text{V} - 0.02\text{V}$) decreases with increasing nanowire diameter.

V. FUTURE WORK

Our future work focuses on the study of photocurrent of single GaN nanowire with and without Au nanoparticles by exposing them to lasers in the range ($400\text{nm} - 700\text{nm}$). This

study will also cover the dependence of photoconductivity with respect to nanowire geometry and intensity of the lasers used.

VI. REFERENCES

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