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Impedance spectroscopy characterization of GaAs nanowire bundles grown by metal-catalyzed molecular beam epitaxy

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ABSTRACT

Vertically aligned GaAs nanowire (NW) bundles grown by gas-source molecular beam epitaxy on an n-doped GaAs substrate by a metal catalysis method and embedded in an insulating matrix (SU8-2) were studied by impedance spectroscopy. The DC current–voltage characteristics measured between Au dot contacts to the NW tips and the substrate exhibited Schottky behavior. A detailed analysis of the impedance data measured in reverse bias conditions is presented, which enables the elimination of the stray capacitance due to the insulating matrix, and the separation of the different contributions to the total admittance from the metal/NW Schottky interface and from the NW region beyond the barrier region. The observed NW conductances and capacitances are shown to be consistent with rough estimates based on the GaAs conductivity and permittivity data and the NW dimensions, and the NW conductance increases as a power law of the frequency. Possible charge transport mechanisms to explain this result are discussed.

1. Introduction

Semiconductor nanowires (NWs) have attracted a great deal of attention due to their unique size-dependent properties [1]. For instance, it has been pointed out that carrier mobilities in NWs should be larger than in bulk materials due to one-dimensional transport. GaAs NWs are particularly interesting in this context because of the important role of this material in photonics and electronics [2]. However, a potential difficulty for NW applications is the determining role that surface states are expected to play in charge transport precisely because of the small NW sizes. It is therefore important to develop electrical characterization methods suitable to study surface states and charge transport in NWs. Here, we report impedance measurements in the 10^3–10^7 Hz frequency (f) range in vertically aligned GaAs NW bundles grown on (0 0 1) n-doped GaAs wafers by Au-catalyzed gas-source molecular beam epitaxy (GS-MBE). Reports on impedance spectroscopy measurements in semiconductor NW systems are relatively scarce in the literature. ZnO NWs bundles have been studied by an electrochemical impedance method and a model was developed to deduce the carrier concentrations in NWs, but the frequency dependence of the impedance was not reported [3,4]. A single SnO NW was studied by impedance spectroscopy at various DC voltages and found to behave as a parallel RC circuit, with a voltage-independent parasitic capacitance and a voltage decreasing resistance [5] while, again, the frequency dependence of the impedance was not discussed. Other impedance measurements were reported where the purpose was to characterize ZnO NW UV sensors under illumination [6] and to understand the electrochemical process kinetics in a lithium ion battery where Si NWs were the electrodes [7]. Hence, our report appears to be the first impedance spectroscopy analysis of a GaAs NW system.

2. Experimental details

GaAs, n-type doped NWs were grown by GS-MBE on n-doped GaAs wafers in a manner described elsewhere [2]. An insulating polymer (Nano^{TM} SU8-2) material was spin coated onto the NW bundles to fill the gap between NWs. The SU8-2 was then etched back to expose the NW tips, as shown in Fig. 1 (some of the shortest NWs remained buried in the polymer). Circular Au dots (800 μm diameter) were then vacuum deposited through a mask to contact the NW tips. From the NW density we estimate that each Au dot contacts about 2×10^7 NWs. Current–voltage characteristics between the GaAs substrate and the top Au contacts showed rectifying behavior with a turn-on voltage (absolute value) of about 1 V (see Fig. 2). Positive voltage is defined here to the case where the substrate is at a positive potential with respect to the top contact.

Impedance characterization in the 10^3–10^7 Hz frequency range was performed using a Hewlett Packard analyzer HP4192A with a modulation voltage of 0.01 V, under reverse bias voltage ($V = 1$ V).

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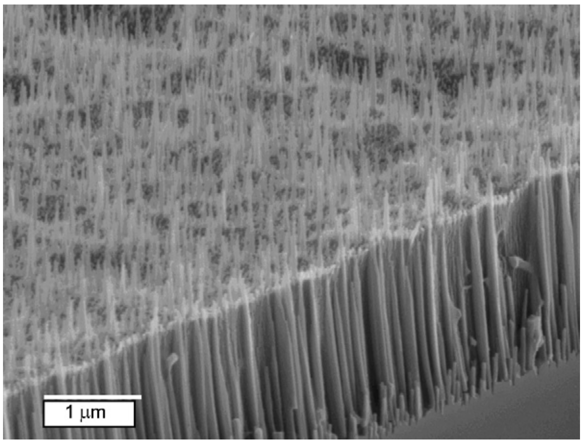

Fig. 1. Scanning electron microscopy (SEM) image showing a tilted cross-sectional view of the GaAs NW sample with SU8-2 spin-coated followed by etching back to expose the NW tips just before Au dot contact deposition.

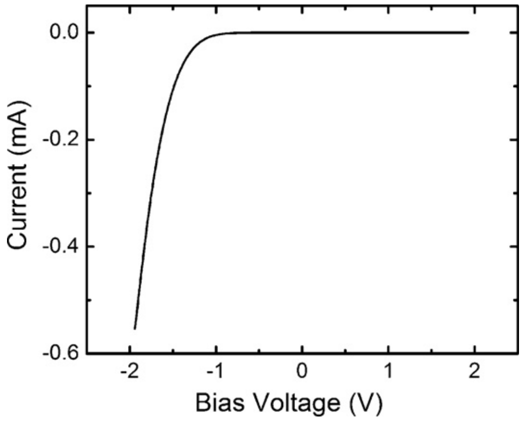

Fig. 2. DC current–voltage characteristics of the GaAs NW device.

3. Results

From the observed polarity of the voltage that leads to reverse bias conditions, it can be deduced that the rectifying behavior of Fig. 2 is consistent with a Schottky barrier being formed at the Au/NW interfaces. Under AC excitation, the device shows resistive and capacitive responses that can be represented by an equivalent circuit (see Fig. 3) with complex admittance Y^*, which comprises contributions from the Schottky contact (impedance Z_C^*), the NWs beyond the barrier region (admittance Y_{NW}^*), and a stray capacitance due to the SU8-2 matrix (represented by $Y_{\text{SU8-2}}^*$):

$$Y^* = Y_{\text{SU8-2}}^* + \frac{1}{Z_C^* + (1/Y_m^*)} \tag{1}$$

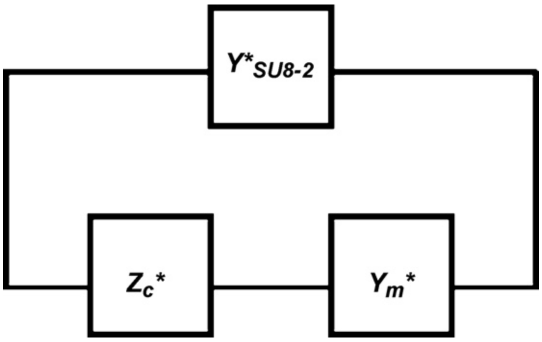

Fig. 3. Equivalent circuit representation of NW sample.

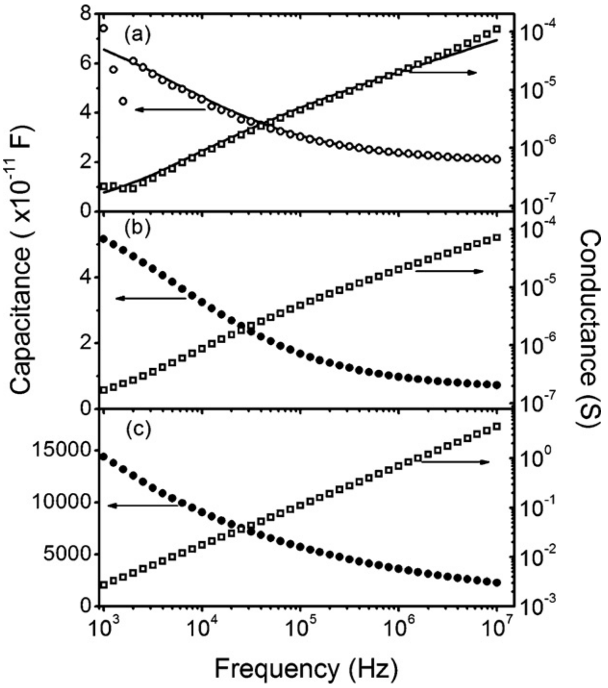

Fig. 4. Capacitance and conductance as a function of the excitation frequency: (a) as determined by impedance measurements of the whole GaAs NW device (symbols), together with the best fit of calculations based on the equivalent circuit shown in Fig. 3 (lines); (b) for the NW bundles beyond the barrier region; and (c) for the Au/NW Schottky interfaces.

To characterize the frequency response of the device, we used the McAdams–Jossinet expression [8,9], which includes a DC contact conductance in parallel with a constant phase angle element. The value obtained for the stray capacitance is constant in the whole measured frequency range, as expected, and equal to $C_{\text{SU8-2}} = 4 \times 10^{-12}$ F, which is small compared to the overall measured capacitance. Fig. 4(a) shows typical capacitance and conductance of the whole device as determined from the measured admittance, and the corresponding best fit of the calculated admittance function for the equivalent circuit (Eq. (1)). The agreement is reasonable. Fig. 4(b) shows the corresponding extracted values of the capacitance and conductance for the NW bundle. From the measured conductance at 10^3 Hz, a conductivity for a single NW of 10^{-5} S/m can be estimated. This value is reasonable considering that the intrinsic conductivity of GaAs is 10^{-6} S/m, that the NWs are doped, and the fact that they may exhibit significant surface in addition to bulk conduction due to their small size. Fig. 4(c) shows the capacitance and conductance for the Schottky contact obtained from the same analysis. The capacitance in this case is much larger, as expected for a space-charge region.

4. Discussion

The NW array capacitance C_{NW} (Fig. 4(b)) decreases with f as expected since NWs cannot respond at very high f. The limiting C_{NW} value should be given by the capacitance associated with the two parallel contacts that impart the electric field on the NWs, i.e. by $C_\infty = \varepsilon N \pi R^2 / L \simeq 10^{-12}$ F, where ε is the permittivity of GaAs, N the number of NWs in the bundle, and R and L are the average NW radius and length, respectively. From the overall capacitance at low f (10^3 Hz), we deduce a capacitance for a single NW of about 2.3×10^{-18} F (ignoring shielding effects between NWs). This value compares reasonably well to the geometric static capacitance expected for a narrow long GaAs cylinder with average NW dimensions [10] ($\approx 10^{-17}$ F), considering that C_{NW} decreases rapidly with f and the neglect of mutual shielding effects between NWs.

The NW overall conductance increases with f (Fig. 4(b)), and the dependence resembles that expected for hopping conduction [11], which sometimes is approximated by f^n in limited frequency ranges, where $n \leq 1$. In the present case, from Fig. 4(b), n changes from 0.75 to 0.58, i.e. it decreases with f as expected from Austin and Mott's hopping theory [12]. A hopping transport in NWs could proceed through localized electronic states due to unpassivated surface atomic configurations (surface traps) at the NW sidewalls, and be enhanced with respect to bulk conduction in the present conditions because of charge depletion in the NWs associated with the surface states or with stacking faults present within the NWs [2,13], and/or because of the prevailing reverse bias conditions. The conductance data in Fig. 4(c) for the metal/NW interface varies as a power law with an exponent of 0.8, consistent with the discussion above, indicating that conduction through localized states may be a factor also in the space-charge region within the NWs. Nevertheless, other transport mechanisms and their dependence on f should be considered in a more general interpretation.

The study of the capacitance and conductance of the GaAs NW bundles for different applied bias is currently under way and the results of a detailed analysis will be published in a forthcoming article.

5. Conclusions

Electrically contacted GaAs NW bundles embedded in an SU8-2 matrix exhibiting Schottky behavior were studied using impedance spectroscopy under reverse bias conditions. A detailed analysis of the impedance data permitted the elimination of the stray capacitance due to the insulating matrix, and the separation of the different contributions to the total admittance from the metal/NW Schottky interface and from the NW region beyond the barrier region. The observed NW conductances and capacitances were shown to be consistent with rough estimates based on the GaAs conductivity and permittivity data and the NW dimensions. Further work is in progress to determine their dependence on bias voltage.

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