Electrical Contacts to Nanomaterials

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The efficient passage of electrical current from an external contact to a nanomaterial is necessary for harnessing characteristics unique to the nanoscale, such as those relevant to energy quantization. However, an intrinsic resistance pertinent to dimensionality crossover and the presence of impurities precludes optimal electrical contact formation. In this review, we first discuss the relevant principles and contact resistance measurement methodologies, with modifications necessary for the nanoscale. Aspects related to the deposition of the contact material are deemed to be crucial. Consequently, the use of focused ion beam (FIB) based deposition, which relies on the ion-induced decomposition of a metalorganic precursor, and which has been frequently utilized for nanoscale contacts is considered in detail.

Keywords: Ohmic Contacts, Schottky Contacts, Focused Ion Beam, Surface States, Nanostructures.

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1. INTRODUCTION

Many foundational aspects of our daily lives at present are based on portable electronic devices. Integral to such devices are the large variety of miniaturized components, such as transistors, many of which are the nanoscale and are electrically responsive. For the efficient functioning of devices, which needs the seamless passage of electrical current (from a battery), optimal electrical contacts are of major importance in interfacing to the nanoscale materials. Indeed, a bad contact may lead to the heating of the device and represents wastage of energy. Consequently, the study of electrical contacts assumes a very important role.

At the very outset, the science and technology of making electrical contacts to nanomaterials differs from the corresponding connections to bulk materials. In this paper, the fundamental issues surrounding optimal electrical contacts to nanomaterials will be presented. The design of optimal contacts will consider the small size scales as well as possible dimensionality differences, which may be pertinent to nanomaterials. While Ohmic contacts, which seamlessly pass electrical current are ideal and desirable, it is observed...
that the dimensionality mismatch to nanomaterials leads to an intrinsic contact resistance. Additionally, material imperfections such as surfaces and defects contribute additional electrical resistance and imply a non-optimal utilization of the nanostructures. In this article, we review such primary (e.g., due to dimensional effects) and secondary (e.g., due to impurities, etc.) influences; the effects of the magnetic fields, e.g., magneto-resistance or superconductivity related effects will not be considered. The aim is to provide a brief overview of the fundamental science and issues underlying contacting nanomaterials with an orientation towards experimental measurement. Typical methodologies for making the contacts, e.g., through metal deposition, will be considered. In particular, a case study of focused ion beam (FIB) deposition (carried out in vacuum based conditions) based on ion-beam induced decomposition of metallicorganic precursors will be discussed. The focus in the latter part of the article is on the use of this technique, in which the relevant advantages and disadvantages will be discussed. However, the paper will start by providing a basis overview of the fundamentals of electrical contacts.

2. ELECTRICAL CONTACTS: FUNDAMENTALS
Traditionally, and until the need arose, contacts as well as the materials to which the contacts are made have been considered from the electrical point of view as three-dimensional. Such an interpretation allowed the use of classical electro-statics/dynamics based methodologies, based on a continuous energy spectrum. However, the consideration of finite size leads to a deviation away from such continuum methods and the invocation of finite length scales and related energy quantization. Such discretization broadly implies that electron motion would now have to be treated as wave-like, considering the famous particle-wave duality principles, and putting the carrier dynamics at the same level as that of electromagnetic waves (photons) or lattice vibrations (phonons). Nevertheless, we will commence our discussion from an Ohm’s law formalism, with

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the measurement of an electrical current passing through the contact-material interface and the material due to an applied potential gradient.

The characterization of electrical behavior in materials is based on recording and diagnosing a response e.g., through an electrical current ($I$) to an applied electrical potential ($V$) difference across the material. A linear relationship between the $V$ and $I$ is the basis of Ohm’s Law. Generally, the $I/V$ ratio is termed the electrical conductance ($G$)—and is the inverse of the resistance ($R = 1/G$). Hence, there is a need to characterize the $G$ or the $R$ of the materials. For high quality electrical contacts, the contact resistance would ideally need to be zero. This is necessary as a finite contact resistance implies an undesirable voltage drop across the contacts and heating, both of which will lead to an energy loss. It is then desired that the contact resistance be as low as possible (or even tending to zero). However, this is not possible in principle, the reasons for which will be discussed next.

The passage of electrical current basically involves from a physical perspective the loss (gain) of electrons (which constitute the current) from a contact to the material. The tendency for the electron loss could be related to the ionization energy and the electron gain energy would be related to the electron affinity. While the concepts of ionization energy and electron affinity have been defined in elementary textbooks as pertinent to atoms, there is a need to extend such concepts from the atomic scale to a solid. In bulk solids, which may be considered as collections of atoms, such to and fro carrier transfer is epitomized through the concept of the work function. An important implication of the work function is that it dictates charge carrier transfer from contact to material.

The work function ($\phi$) is conventionally defined as the energy necessary to remove an electron from a bulk solid and is characteristic of particular material. The $\phi$ is measured through the energy necessary to free an electron from the Fermi level ($E_F$) and making the electron free implies moving the electron to a vacuum state; the $E_F$ here is related to the highest occupied energy level of electrons. It is the relative $\phi$ difference (in the absence of an external voltage) that dictates whether electron transfer occurs to/from a material adjacent to a contact, i.e., if $\phi_{\text{contact}} < \phi_{\text{material}}$, then electron movement occurs from the contact to the material, whereas with $\phi_{\text{contact}} > \phi_{\text{material}}$, electron transfer is opposite (from the material to the contact). From a quantitative perspective, it may then be expected that the energy barrier for electron transfer from the contact to the material—would be equal to $|\phi_{\text{contact}} - \phi_{\text{material}}|$. Hence the energy barrier $\Delta$, for charge injection from a contact (considered an infinite source) to a material would be:

$$\Delta = |\phi_{\text{contact}} - \phi_{\text{material}}|$$

(1)

However, such an idealized relation fails even for any practical (finite-sized) material due to the inevitable presence of a surface. The section that follows will aim to give an explanation as to why this might be the case.

### 2.1. The Electrical Contact-Material Interface

Figure 1 indicates a typical metal electrode (on the right)—material (left) interface and the parameters that need to be considered when evaluating the contacts. Electrical current may flow from/to the contact to/from the material only through carriers surmounting the intrinsic barrier, e.g., either through classical thermal excitation or quantum mechanical tunneling. As shown, the material in this example is a semiconductor and thus possesses an energy gap between a lower energy valence band (VB) and a higher energy conduction band (CB). The VB and CB is an agglomeration (i.e., band) of energy levels delineating the occupied and unoccupied electrons in the material. It should also be noted that we are considering semiconductors as prototypes of bulk materials, for three main reasons, i.e.,

1. for their technological importance, e.g., Silicon based semiconductors are at the heart of the microelectronics revolution,
2. many nanomaterials can be modeled as semiconductors, and finally
3. metal-metal contacts are typically low resistance.
Both n-type semiconductors (which have electrons as the electrical carriers) as well as p-type semiconductors (where electrical conduction occurs through empty electron states, i.e., holes) will be discussed. The construction of energy band diagrams in general (as illustrated in Fig. 1) typically requires the constancy of electrochemical potential as well as the vacuum energies in equilibrium, throughout a connected system. Such diagrams can be considered to represent materials systems extending to chains of atoms characteristic of nanoscale materials.

Figure 1 is drawn for the case of \( \phi_{\text{contact}} > \phi_{\text{material}} \) with \( \phi_{\text{contact}} = \phi_{\text{m}} \) the work function of the metal (m) electrode on the right, and represents electron transfer from the material to the electrode contact and consequently a deficit of electron carriers resulting in the formation of holes, populating the VB. The equivalent energy for removal of an electron is termed the electron affinity (\( \chi \)). A Fermi energy level (\( E_F \)) is also defined, which is the highest energy level of electron occupancy. The position of \( E_F \) relative to the CB is dictated by the level of carrier doping, i.e., for a metal, \( E_F \) would be overlapping the CB or the VB, while for a perfect insulator (where the number of electrons in the CB is zero) the \( E_F \) would be exactly in between the CB and the VB. Electron passage from the material to the contact induces an upward energy band bending of the CB by \( V_{BO} \) (due to the equivalent reduction of electrons in the material) which presents an energy barrier (\( \Delta \phi_{\text{m}} \)) for motion of the electrons to/from the material. The barrier is further reduced by \( \Delta \phi_{\text{m}} \) due to the impressed electric field in the material formed due to electron transfer from the material to the electrode contact. The subsequent voltage drop across the electrical double-layer is indicated by \( \Delta \phi_{\text{m}} \).

If \( \phi_{\text{contact}} \leq \phi_{\text{material}} \), then a band bending of the opposite curvature would be the result with excess electrons in the CB near the interface. Energy band diagrams (as illustrated in Fig. 1) both in equilibrium as well as with externally applied voltage are fundamental to the understanding of electrical contacts and have been widely discussed.

### 2.2. Electrical Carriers Need to Surmount the Barrier at the Contact—Material Interface for the Passage of Electrical Current

As shown in Figure 1, electrical current from (to) the contact to (from) the material can only occur through carriers surmounting the intrinsic barrier at the contact/material interface. These in turn need (i) classical perturbing forces or fluctuations, i.e., temperature induced excitation of the carriers above the barrier (thermionic emission—of carriers from/into the contact) or (ii) the additional influence of applied electrical fields, or (iii) decreased barrier width aiding the quantum mechanical tunneling of carriers through the barrier (often considered as field emission).

When temperature or applied electric field is increased the current then increases exponentially. In addition to the height of the barrier, the width of the barrier (approximately the length over which the band bending occurs) is also relevant: this is termed as a carrier depletion width (\( W \)). A well-known relationship of the form:

\[
W \sim \sqrt{e \Delta \phi_{\text{m}} / \epsilon N_d}
\]

(where parameters indicated in Figure 1 and \( N_d \) being the carrier concentration in the region) is used as a measure of the distance through which the electrical carriers have to traverse to reach the interface (thus directly related to the resistance experienced by the carriers). Tunneling, for example, is aided through a narrow \( W \), which is obtained through increasing the \( N_d \). This can be achieved through a heavily doped semiconductor (> 10²⁰/cm³), thus approaching a “metallic” condition which is most desirable to obtain low resistance ohmic contacts.

As with any material, the finite size of materials and presence of defects will affect the material properties. In relation to Figure 1, this will affect the work function and thus imposes correction corrections to work function oriented paradigms for charge transfer; this will be further discussed here. In relation to size, it is obvious that any material has a finite size and a surface. The surface represents the termination of bulk material and thus composed of surface states that are distinct from bulk states, e.g., in terms of number of chemical bonds or due to the presence of foreign atoms from adsorbates, etc. As the surface area to volume ratio increases (as is the case for nanomaterials), the size of the material decreases the consideration of surfaces (and surface states) assumes an even greater importance. Indeed, it is sometimes proclaimed that nanomaterials are “all surface”. It is then typically found that the interactions between the surface and bulk energy levels results in the formation of hybrid states, in the spirit of the Debye-Hückel model are distinct from either levels. For example, in a semiconductor-metal contact, hybrid states referred to as “Tamm states” can be found in the bandgap region (between the VB and the CB) of Figure 1, located approximately at one-third of the bandgap energy (\( E_g \)) from the valence band edge. The extent of state filling is considered through an energy \( \phi_{\text{m}} \)—see Figure 1 is measured from the VB edge, specifying the energy below which all the surface states are filled so as to ensure charge neutrality at the semiconductor surface. The remaining difference—between the Fermi level and \( \phi_{\text{m}} \), represents the net surface state charge density \( (Q_{SS}) \) which together with the charge in the depletion layer of the semiconductor \( (Q_{SC}) \) forms the total charge present in the material. An equal and opposite charge, of magnitude \( Q_m = -[Q_{SS} + Q_{SC}] \), would now be induced in the metal in a very small interfacial layer of thickness: \( \delta \).

The \( Q_m \) stored in the \( \delta \) as well as the relative dielectric permittivity \( (\epsilon_r) \) of the interfacial layer could be used to infer the potential drop (\( \Delta \phi_{\text{m}} \)) through the application of

\[
\]
3. ELECTRICAL CONTACTS AT THE NANOSCALE

As in bulk materials, the electrical characteristics of nanoscale materials are also monitored through the $I/V$ ratio in terms of the electrical conductance ($G$) or the resistance ($R = 1/G$). However, the nanoscale size and dimensionality may mean that resistance measurements are not straightforward. While bulk objects are inherently three-dimensional (3-D), nano-objects have a lower dimensionality, i.e., $D < 3$ resulting in dimensionality crossover effects, when making contacts to nanomaterials.

3.1. Peculiarities of the Nanoscale

While the term nanoscale has been used to refer to size ranges of the order of 1–100 nm, a nano-object has been defined as a material with one, two or three external dimensions in the nanoscale.\textsuperscript{15} Examples of nano-objects include atom thick graphene sheets,\textsuperscript{16, 17} cylindrical carbon nanotubes,\textsuperscript{18, 19} and quantum dots.\textsuperscript{20} It is not trivial to ensure good electrical contacts with such objects due to the difference in geometry as well as the size scales involved and the relevant issues will now be discussed.

For instance, a low contact resistance may be ensured only through a contact conformal with the shape of the nano-object. Additionally, in bulk materials/objects there is a continuous distribution of energy, which means that the electrical carriers can easily move between energy levels in the bulk-like contact to the material. However, lower dimensional objects have quantized/discrete energy levels. For example, in graphene (which is a 2-D material), the energy levels are continuous in the plane of the sheet but discrete perpendicular to the sheet. While classical electrodynamics would be sufficient to describe the carrier motion along the cylinder length in a 1-D carbon nanotube (CNT), a discrete diameter indicates the necessity of a quantum mechanical description along the two dimensions orthogonal to the length. Such energy discretization is not evident in all nanomaterials, e.g., silicon nanowires.\textsuperscript{21} For traditional 3-D materials such energy discretization is irrelevant as continuum considerations imply that any part of the material behaves as any other, while for lower dimensional material each part could be considered distinct. While bulk or a quantum wire, of a given material, may have the same carrier density ($= \text{number of carriers/unit volume}$) the arrangement of the carriers (reckoned in terms of the density of states: the DOS) would be different in the two manifestations, e.g., more (less) electrons are accommodated at lower (higher) energies in the quantum wire. This corresponds to the transition to discrete (atomic) energy levels in nanostructures. The mathematical aspects of the arrangement of the electrons in nanostructures \textit{vis-à-vis} bulk materials have been well-discussed elsewhere.\textsuperscript{22}

A length scale demarcating the classical and the quantum regimes is the carrier wavelength ($\lambda_c$) related to the energy, $E$, through $E = \hbar c/\lambda_c$, where $\hbar$ is the Planck constant ($= 2\pi\hbar$, $\approx 6.626 \times 10^{-34}$ J·s), and $c$ is the carrier
group velocity. A case for 1-D behavior is obtained when
for a particular carrier of energy \( E \), the diameter is of the
order of/less than \( \lambda_c \). A typical value for the \( c \) is the Fermi
velocity \( (v_F) \), which is proportional to the carrier concen-
tration and the dimensionality varying as \( n^{D} \). However,
such a length scale demarcation is fraught with prac-
tical difficulty in that the \( c \) is related to the electron/hole
band-structure and may not be readily computed when the
precise orientation of the nanostructure is in doubt.

Additional peculiarities of the nanoscale are related to
other quantum-mechanical effects, e.g., quantization of the
electrical resistance to integer multiples of \( \hbar/e^2 \) as
in the quantum Hall effect in 2-D electron gases \( ^5 \) or
graphene sheets. \( ^{17} \) As such phenomena are typically man-
ifested through macroscale (3-D) measurements, the electrical
characterization of nanoscale materials necessarily
implies a dimensionality crossover. While the basic aspect
of electrical contacts, i.e., there should be corresponding
energy levels in the nanomaterial between the source and
the sink in the presence of electrical voltage, with an elec-
trical resistance depending on the mismatch and the energy
level spread, such an ideal is rarely seen in real nanoscale
electrical contacts. The reason for such non-idealities, typi-
ically yielding larger electrical resistances, can be traced
to defects, either intrinsic to the material, e.g., surface
states, impurities, adsorbates, etc. or extrinsic—due to the
methodologies used for depositing the electrical contacts.
Intrinsic defects typically induce non-Ohmic/Schottky con-
tacts (Section 2.5), whereas the electrical current to and
from the nanomaterial is different. However, the dele-
terious influence of extrinsic defects may be gradually
improved through improved methodologies of depositing
the contacts.

3.2. Optimal Nanoscale Electrical Contacts Reveal
New Physical Phenomena

Non-optimal electrical contacts tend to obscure the
genuine understanding and characterization of unique
nanoscale properties as well as pertinent quantum mechan-
ical phenomena. For example, electrons in bulk materi-
als have been described in terms of a fluid (the Fermi
liquid \( ^2 \)) penetrating the structure. However, such charac-
terization is incorrect for nanomaterials, and modifications
to the Fermi liquid behavior \( ^2 \) must be considered due to
electron-electron interactions. A Lifshitz—liquid behav-
ior has been observed in 1-D metallic nanotubes, \( ^{23} \) where the
\( G \sim V^\alpha \) with \( \alpha \) as an interaction parameter with a
value between zero and unity (for a Fermi liquid \( \alpha = 1 \)).
To provide another example of the utility of good electrical
contacts/high interface transparency, characteristics of
Andreev reflection (where an incident electron at the con-
tact is converted into a Cooper pair with the concomitant
introduction of a reflected hole) were noted along with the
possibility of superconductivity. \( ^{24} \) However, when the
contacts are relatively opaque to incident currents, such
phenomena may not be observed. From a technological
perspective, additional contact resistance leads to energy
dissipation through Joule heating which may be quite
severe at the nanoscale and introduce undesirable aux-
iliary thermoelectric effects. \( ^{25} \) Additionally, intrinsic carrier
characteristics such as the electron/hole mobility (the ratio of the
carrier velocity to the applied electric field) hinge on the
accurate determination of the net resistance. The con-
tact resistance and capacitance can also set the operating
speeds/frequency scales of a nanomaterial based device,
e.g., for a single walled CNT frequencies of the order of
6.3 THz (= 1/2\( \pi RC \)—say, corresponding to a minimum
resistance of 6.5 k\( \Omega \), i.e., \( h/4e^2 \) and a capacitance value
of 0.1 aF. Internal motion of the electrons in the nanomate-
rial may lead to kinetic inductance \( ^{22} \), \( ^{26} \) phenomena which
adds to the nominal electrostatic inductance and could be
probed through contacts of low resistance.

3.3. Modification of Electrical Contact Resistance Due
To Ambient Control

As we have previously discussed (Section 2.4), nanomate-
rials may be considered to be "all surface," due to their
much larger surface area to volume ratio compared to
bulk materials, and are particularly susceptible to influ-
ence as well as contamination from the ambient. For ex-
ample, it is experimentally observed that semiconduct-
ing single wall CNTs (SWNTs) and many other nanomate-
rials are usually We, due to the influence of the ambient
oxygen \( ^{27} \) which abstracts electrons from the CNT due to
its high electronegativity (electron-acceptor), and in turn
imparts generates hole \( ^{28} \) carriers into the materials. Alter-
ately, exposing SWNTs to electron-donating agents such as
nitrogen \( ^{29} \) and alkali metal dopants \( ^{30} \) results in \( n \)-type
doping. From basic organic chemistry, \( ^{31} \) it would also
appear that the activating (due to \( \cdot OH, \cdot NH_2, \cdot CH_3 \), etc.)
or deactivating (due to halogens, \( \cdot NO_2, \cdot COOH, \cdot CN \), etc.)
effects of substituents and functionalizing agents on
nanotubes or graphene could also play a major influence
and a careful control of the ambient would be necessary
for interpreting experimental results. It was determined
\( ^{30} \) that the annealing in vacuum, through oxygen removal
(or doping the surface with alkali metals) converts \( p \)-type
CNT based devices to \( n \)-type, and results in an upward
shift in the Fermi energy from the valence band to mid-
gap. Evidence for charge transfer in doped CNT bundles
exposed to electron donors (K, Rb) and electron acceptor
(Br, I) atoms was also seen through Raman spectroscopy
investigations. \( ^{32} \)

However, if the physisorption of the oxygen on the
nanostructure is weak and unlikely to result in charge
transfer, the observed conductivity changes may not be
intrinsic to the nanostructure \( ^{33} \) and the interactions with
the much larger electrode contacts should be investigated.
The changes in the contact metal work function and their
influence on the Schottky barrier may also modulate the
electrical conductivity. A phenomenological model was advanced to explain the $p$-type to $n$-type conversion, where the concentration of oxygen is proportional to, and determines the position of the $E_F$ at the metal-CNT interface. Such an effect changes the line-up of the bands at the interface but does not involve the bulk of the nanostructure. When the $E_F$ at the junction is close to the center of the band gap, the barrier allows tunneling and ambipolar transport—involving both electrons and holes—was observed. With Au contacts in air, only holes can be injected into the device, while annealing/removal of oxygen results in only electrons being injected due to the high hole injection barriers.

3.4. Proximity and Dimensionality Effects on Carrier Transfer from the Contact

The specific nanomaterial bandstructure (see Fig. 1) does not seem to be particularly important in terms of carrier transfer, as movement occurs between closely spaced energy levels at the interface. However, the proximity of the metal to the nanostructure, e.g., graphene, seems to be critical along with the work-function differences in carrier movement. Figure 2(a) indicates work function based carrier transfer from a metal contact (with a work function: $\phi_M$) to a graphene (with a work function: $\phi_G$) seemingly independent of the linear energy dispersion of the latter. However, the number of carriers ($\Delta n$) induced in the latter: Figure 2(b), at a given work function difference ($\Delta \phi$) is related to the metal contact-graphene separation distance ($d$).

It would nominally be expected that as the $\phi$ graphene is $\sim 4.5$ eV, a transition from $p$-type to $n$-type doping in graphene would occur when the contact metal work function is decreased from below 4.5 eV to above this value. However, it was noted\(^{35}\) that a metal-graphene chemical interaction might play a role when equilibrium separation distances (e.g., of the order of typical C-C layer spacing of $\sim 0.34$ nm in graphite). The consequent tendency towards bond formation induces a potential barrier of $\sim 0.9$ eV that has to be overcome implying that the $p$-type to $n$-type transition occurs instead at a larger value of $\sim 5.4$ eV. Indeed, the value of $\sim 4.5$ eV for the transition was found to be valid only at larger metal-graphene distances, say of the order of 0.5 nm. Even weak bonding of metals, such as Al, Ag, Cu, Au, and Pt to graphene could shift the transition point. However, stronger bonding of metals, such as Co, Ni, Pd, or Ti inducing graphene chemisorption would result in a much larger work function lowering of the metals\(^{36}\)—by as much as 1.5 eV. Consequently, a buffer layer, e.g., Ti of sufficient thickness, say $\sim 5$ nm, between the contact electrode and the graphene has been advocated to ensure better contacts and enhance the contact conductance. Alternatively, a softer contacting scheme where the metal minimally perturbs the graphene or the nanotubes has been considered\(^{37}\) for better Ohmic contacts. The observation that Pd is typically found to form better contacts, e.g., as in the manifestation of ballistic effects in nanostructures,\(^{38}\) has been used for justification of such a premise with the underlying rationale that the metal just wet the surface without significantly perturbing the electronic structure of the lower dimensional materials as would occur, for example, through chemisorption. The effective contact length ($L_{\text{eff}}$; see Section 4.1) would be a relevant parameter and may need to be larger than a critical material dependent value to ensure maximal conductance.\(^{39}\)

4. ELECTRICAL CARRIER TRANSPORT IN NANOSCALE DEVICES

The kinetics of carrier transport from the contact to the nanomaterial is characterized through the relative values of the thermodynamic attributes, such as the temperature: $T$, and the relevant energy scales (such as depicted in Fig. 1), as well as dynamic attributes such as the scattering time or the related mean free path. A determination of the band structure allows for the calculation of an energy dependent conductivity ($\sigma_3D$) for the graphene sheet/a nanotube surface, as $\sigma_3D = (2e^2/h)(E/h\nu)l_e$. The elastic scattering length\(^{40}\) ($l_e$) of the carriers is proportional to the electron-phonon (lattice vibration) scattering.
and generally increases with decreasing temperature (usually, $l_e \sim T^{-p}$, with $p > 1$). The obtained resistances are inversely proportional to the scattering lengths, e.g., in 50 nm x 50 nm copper traces, the resistivity was approximately twice the bulk value and hence impose limitations\(^4\) in power dissipation and operating speeds. The possibility of ballistic (collision-free or equivalently a very large $l_e$ for carrier transport\(^5\)) motion together with large carrier mobility allows for a large carrier mean free path (say, $> 1 \mu m$) due to the reduced phase space for scattering in lower dimensional structures. The electrical conductivity of nanostructures may be broadly classified, e.g., with respect to temperature or the thermal energy (parameterized through $k_B T$, where $k_B$ is the Boltzmann constant), into two regimes:

(1) \textit{Low temperatures} ($k_B T < E_F$); where in the expression for $\sigma_{2D}$ above, the energy ($E$) is replaced by $E_F$. The conductivity in this regime is \textit{metallic}. A finite zero-temperature value, the magnitude of which is determined by the static disorder, is obtained.

(2) \textit{High temperatures} ($k_B T > E_F$); where in the expression for $\sigma_{2D}$, the $E$ is replaced by $k_B T$. The conductivity, and the carrier density, is then directly proportional to $T$.

4.1. Intrinsic Electrical Resistance of Nanostructures

At the very outset, it is not trivial to \textit{measure} the intrinsic resistance of a nanostructure, such as a nanotube. For example, any contact in addition to those at the very ends of the tube (say, for a four-terminal measurement) may be thought to destroy\(^6\) the one-dimensional nature of the CNT and make a true interpretation difficult. Theoretically, for a strictly one-dimensional system the Landauer formula predicts an intrinsic resistance ($R_{in}$), independent of the length, to be equal to $(h/e^2)(1/Tr(E_F))$ which translates to a resistance of $\sim 25.8 \Omega$ assuming perfect transmission ($Tr$) through ideal Ohmic contacts, i.e., $Tr (E_F)$ equal to one. Such a contact resistance arises from an intrinsic mismatch between the external contacts to the wire (which are of higher dimensionality) and the one-dimensional nanotube system and is \textit{always} present. When one takes individually into account both the two-fold spin and band degeneracy of a nanotube the intrinsic resistance ($R_{in}$) now becomes $(h/4e^2)(1/Tr(E_F))$, i.e., $\sim 6.5 \Omega$.

However, in the above discussion, we have not yet considered the contribution of the external contacts. When we do consider the transmission through the contacts into the one-dimensional channel and then to the next contact, it can be derived that,\(^5\) $Tr = (l_e/\sqrt{l_e + L})$, where $L$ is the length of the one-dimensional conductor. The resistance is now equal to $(h/4e^2)((l_e + L)/l_e) = (h/4e^2)(1 + (l_e/L))$. The first term represents $R_{int}$ while the second term denotes an Ohmic resistance ($R_{Ohmic}$) associated with scattering. In the presence of dynamically scattering impurities, such as acoustical or optical phonons, which are inevitably present at any temperature above 0 K, such an Ohmic resistance should definitely be considered. For example, in short ($\sim 0.5 \mu m$) CNTs the acoustic phonon scattering (of time scale $\sim 0.4$ ps) is too slow and only the optical phonons (with smaller lifetime $\sim 0.02$ ps) contribute to carrier thermalization during a typical transit time of $\sim 0.6$ ps, implying a carrier velocity ($v$) of $\sim 8.10^5$ m/s. On the other hand, in longer CNTs ($> 10 \mu m$, say) with longer transit times, a complete carrier relaxation/equilibration is obtained. It is interesting to consider the limiting cases of a large mean free path ($l_e \to \infty$) or a small length scale ($L \to 0$) i.e., in the ballistic regime, where the Ohmic resistance vanishes. Finally, the material resistance of the contacts due to intrinsic or extrinsic impurities (see Section 3.1) contributes an additional term: $R_c$. The total resistance as measured in an external circuit would now be:

$$R_{meas} = R_{int} + R_{Ohmic} + R_c$$  \hspace{1cm} (3)

These considerations imply that a minimum resistance of $h/4e^2$ ($\sim 6.5 \Omega$) is only present in a nanostructure with a single channel (corresponding to a discrete energy level) of conduction. Consequently, there would be a natural impedance mismatch between nanotubes ($\sim kT$) and macroscopic circuitry and packaging (which is typically configured with an input impedance of 50 $\Omega$) and poses an interfacing problem in nano-devices. Possible ways, which may be currently impractical, around such problems involves the construction of a system completely out of graded lower-dimensional nanostructures or through \textit{wireless} contact using inductive means, the latter being more effective at higher frequencies, due to the contributions of the kinetic inductance\(^7\) (see Section 3.2).

4.2. Measured Electrical Resistance of Nanostructures

In practice, imperfect contacts (which lead to a $Tr < 1$) and the presence of impurities lead to larger resistance values, while deviations from strict one-dimensionality or multiple channels of conduction (as in a multi-walled CNTs: MWNTs) could lead to smaller numbers for the resistance. These observations primarily account for the large discrepancy of the numerical value of the nanostructure resistances reported in literature. The electrical conductivity of MWNTs can be modeled to be comparable with that of independent graphene sheets. When the tube diameter is smaller than the $l_e$, the one-dimensional ballistic transport predominates, while, if the diameter is larger than $l_e$, the current flow could be described as diffusive/two-dimensional transport.

Generally, the mismatch between a nanomaterial and an external bulk/3-D contact would be expected to be larger the greater the discrepancy in the nanostructure dimensionality, i.e., the largest intrinsic contact resistance could be obtained for a 0-D/quantum-dot like system. Indeed, the notion of the electrical resistance of a 0-D system is in meaningless due to the absence of a dynamic current.
Instead, electron addition/subtraction would be manifested through Coulomb Blockade effects, where the addition of each extra electron results in an enormous charging energy ($e^2/2C$), due to the inherently small capacitance ($C$ in the fF: $10^{-15}$ fF range). A peak in the conductance, as well as conductance fluctuations corresponding to the addition of each extra electron has been observed. Universal conductance fluctuations of magnitude $e^2/h$, characteristic of stochastic, quantum interference effects in the sample may also be observed. Such effects may also be seen in higher dimensional nanostructures, when $k_BT < E_F$, i.e., a nanotube grapheme ribbon which may behave as a single/ array of quantum dots in the presence of disorder. Such studies have served to elucidate the nature of transport in nanotubes vis-à-vis resonant tunneling from the electrodes to discrete energy levels in the nanotubes and the coherence of electron currents. However, significant deviations from the simple Coulomb blockade picture are mediated through the electronic correlations and Luttinger liquid behavior, where electron spin flips may have to be considered as well. Coulomb Blockade effects, which are almost always observed in SWNTs at low temperatures, do not seem to be particularly relevant for MWNTs.

For electrical contacts to multiple graphene layers or MWNTs, multiple modes, say $N$, of conduction—implying electrical resistances in parallel, would be expected to reduce the intrinsic resistance to $h/4Ne^2$. Coaxial nanowire structures, where either the core or shell is doped may also be effective in reducing carrier scattering effects. However, it has been determined that for a coaxial arrangement of MWNTs, the electrical current flow occurs only through the outermost nanotube. Also, while the mutual interaction between the adjacent coaxial cylinders/sheets might be very small (of the order of 10 meV compared to room temperature thermal energies of the order of ~26 meV), it cannot be completely neglected, and makes for a richer band structure in contrast to SWNTs and comparable to graphite (where the inter-plane coupling is also ~10 meV). Inter-tube coupling (which depends inversely with the MWNT diameter) can also significantly affect the band structure. For instance, in a double walled nanotube, one metallic and the other semiconducting, low energy properties characteristic of metallic tubes predominate while if both the constituent tubes are metallic, a much more complicated situation in terms of band crossings can arise.

5. ANALYSES AND ESTIMATES OF THE CONTACT RESISTANCE

We have seen that there is an intrinsic contribution to the contact-nano-object resistance due to the dimensionality crossover, i.e., typically through a decrease in the number of current carrying modes from the 3-D contact to the lower dimensional nanomaterial. Additional interfacial parasitic contact resistance ($R_c$) may also be computed through a two-electrode system geometry from the intercept of the measured resistance ($R_{\text{meas}}$) plotted as a function of material/device length ($L$), e.g., from $R_{\text{meas}} = 2R_c + R(L)$. In a three-electrode system (such as field effect transistors: FETs) the $R_{\text{meas}}$ is tallied as a function of the length of the channel ($L = L_{\text{channel}}$) where again, the linear extrapolation of the measured resistance, to zero channel length would be the $R_c$. A specific contact resistance is obtained by $r_c = R_c/A$, where $R_c$ is the contact resistance for current flow perpendicular to a contact of area $A$ with units of $\Omega \cdot \text{cm}^2$ can then be defined. It should be noted that the $r_c$ is a better measure as the $R_c$ is contact size dependent and needs a standard measure, say $\Omega \cdot \text{cm}$ or $\Omega \cdot \text{mm}$, for comparison between different device configurations. By way of quantitative estimates, the $r_c$ at a metal-Si interface was theoretically shown to have a lower limit of $\sim 10^{-8} \Omega \cdot \text{cm}^2$. Experimental observations have shown that for even optimally doped nanowires (NWs) the $r_c$ values are two-three orders of magnitude higher. This would imply for a 10 nm diameter Si nanowire, a contact resistance ($R_c = r_c/A$, where $A$ is the circular contact area) of the order of 5 kΩ and which would increase with decreasing nanowire diameter. Additionally, as such low $r_c$ values would be typically obtained at high carrier doping concentrations ($\sim 10^{20} / \text{cm}^3$), there is a greater scope for mutual electrical carrier interactions, which adversely affects the carrier mobility. However, $r_c$ of metal-epitaxial graphene interfaces was indicated to be $\sim 10^{-7} \Omega \cdot \text{cm}^2$ or even less at $10^{-8} \Omega \cdot \text{cm}^2$.

While influence of the contacts may mostly be eliminated in four-electrode resistance measurement configurations—where two leads are used for sending the current and two other electrodes are employed for the voltage measurement (using an infinite resistance voltmeter), such measurements are not often possible in practice and may disrupt the dimensionality of the nanostructures. In terms of modeling the placement of a contact onto the nanomaterial, an often used concept is the transmission line model where current passage along the length of the contact into the nanomaterial is probed, in terms of a distributed impedance.

5.1. Transmission Line Models

It was noted that generally for a planar metal (considered to be an equipotential plane of infinitesimal thickness) contact to a material, the current input must consider both the (a) interfacial resistance between the metal and the material, as well as (b) the finite thickness of the material. Two models are in vogue to describe the individual situations, i.e., while a Kennedy-Murley (KM) approximation neglects the interfacial resistance, a transmission line model (TLM: Fig. 3) does not take into account the finite interface thickness. Considering first the TLM, the top electrode and the bottom material surface constitute two elements of the TL. Then, using
standard transmission line theory, the currents and voltages at any point along the quasi-1D TL may be derived and the resistances/impedances computed from their ratio.

TLM based derivations then underlie the formulation of the contact resistivity-specific contact resistance for current flow perpendicular to a contact of area \( A \) (\( r_c = R_c \cdot A \)), say for 2-D materials, such as graphene, (as we consider planar configurations), where:

\[
R_c \cdot W = \sqrt{r_c \cdot r_{2D}} \cdot \text{coth} \left( L_{con} \sqrt{\frac{r_{2D}}{r_c}} \right)
\]

The \( L_{con} \) is the actual length of the contact (also referred to as the transfer length: \( L_t \)) and the contact resistivity of the 2-D material is also involved, e.g., \( r_{2D} = r_{\text{graphene}} \). Further details on the derivation, and the underlying assumptions, are given in the appropriate references. Extensions to the TLM, considering a finite thickness of an interface layer (consisting for example, of a homogeneously doped semiconductor layer in between the semiconductor and the contact electrode) have been used to bridge the TLM to the KM models as well as to obtain greater correspondence to experiment. In the specific case of a FET, for example, the TLM assumes a linear potential drop across the channel, and the \( R_{\text{meas}} = R_c + L/(W \cdot \mu \cdot C \cdot |V_{gS} - V_{ds}|) \), where \( L/W \) is the length/width ratio of the channel, \( \mu \) is the contact-resistance free carrier mobility, \( C \) is the gate insulation capacitance, and \( V_{gS} \) and the \( V_{ds} \) represent the regulating gate-source and the drive drain-source bias, respectively. For graphene based FETs, ultra-low resistance Ohmic contacts have been reported with a contact resistivity of \( 10 \text{ m}\Omega \cdot \text{cm}^{-2} \) (i.e., the resistance of low resistance metals such as Ag or Cu are \( \sim 1 \mu \Omega \cdot \text{cm} \)). It was been suggested that doping of the graphene may increase the number of conducting channels and would help decrease the contact resistivity further.

Additionally, whether the carriers move diffusively or ballistically in the graphene after injection must be considered through corrections based on the carrier scattering length or the metal-graphene coupling length \( (L_m) \), relative to the actual physical length of the contact \( (L_{\text{con}}) \). For example, if \( L_{\text{con}} > L_m \), then the carrier transfer is complete while on the other hand, if \( L_m > L_{\text{con}} \), then the transmission probability would be reduced. The \( L_m \) is a function of the inhomogeneous and homogeneous lifetime broadening of the graphene states under the metal, and is in turn related to the contact metal-graphene coupling, the DOS of the metal states, etc. The scaling of the conductance with the \( L_{\text{con}} \) was also noted for the metal contact coupling with carbon nanotubes (considering that a larger diameter nanotube was akin to a graphene sheet), where chirality was observed to play a role as well with better coupling to an armchair type nanotube compared to a zigzag nanotube. Interestingly, disorder was posited to enhance the coupling due to the possibility of a greater variety of coupling mechanisms.

6. PRACTICAL METHODOLOGIES FOR CONTACT METAL DEPOSITION ON NANOSTRUCTURES

Electrical contacts have been made to nanostructured materials both through a relatively large-scale non-focused vacuum based deposition of metal as well as more localized placement of a metal through decomposition of a metalloorganic precursor using focused ion beam (FIB) based deposition. In this section, we discuss both approaches with a detailed study of the latter approach.

6.1. The Optimization of Physical or Chemical Vapor Deposited Contacts

A major vagary, and a recurrent theme in day-to-day experimental measurements, of the electrical properties of nanomaterials placed on/below metal electrode contact on substrates is the issue of non-reliable Ohmic contacts. The metallic contacts are typically deposited through physical methods (e.g., sputtering, electron-beam evaporation, etc.) or chemical vapor deposition (CVD) methodologies (e.g., involving metalloorganic precursors or enhancements such as plasma, etc.). A summary of such methods, and the relative advantages and drawbacks has been extensively documented.

From the viewpoint of obtaining optimal electrical contact resistance, it has been previously discussed (see Section 4.1) that the minimum intrinsic resistance of a nanostructure, with a single mode of electrical conduction would be of the order of \( h/4e^2 \approx 6.5 \text{ k}\Omega \). However, high contact/Ohmic resistances usually prevent the observation of such values. The granularity of the metal electrodes and contamination at the interface are some obstacles to the realization of good contacts. While several methods such as thermal and electron-beam induced annealing for reducing defects or ultra-violet/ozone based treatments—for the removal of organic impurities, have been proposed, they have had little impact in terms of
consistent success. A notable study in this regard is the use of Pd/Pt contacts, and in situ modification of the electrode work function through hydrogen annealing treatments, through which Ohmic behavior was induced with ballistic transport with the measured nanotube resistance approaching the theoretical minimum. Such behavior, characteristic of reflection less contacts, were even used to construct devices with perfect electron coherence, such as a Fabry-Perot interferometer.

6.2. Focused Ion Beam Deposition (FIB)

FIB based techniques are of wide use in the semiconductor industry, and play a critical role in applications including, e.g., metal deposition induced repair of integrated circuits, cross section imaging of micro-fabricated devices, electron microscopy (EM) sample preparation, etc. FIB induced metal deposition has also been extensively used in electrical connection and concomitant measurements of nanostructures such as nano-tubes wires, quantum dots, and related devices.

6.2.1. Principles of Focused Ion Beam Based Electrical Contact Deposition

Typically, for metal deposition Ga+ constituted ion beams serve to decompose the metalorganic (MO) precursors—which serve as the source for the metal. Figure 4 indicates the schematic of a typical FIB setup.

The FIB metal deposition process (see Fig. 4) involves heating (typically to \(~50\) °C) the relevant MO precursor in a gas reservoir adjacent to the EM chamber, subsequent to which MO vapor is controllably passed, through a gas nozzle, into the vacuum chamber. It is thought that the vapor molecules adsorb onto the substrate, and are then decomposed through interaction with the ion beam. The decomposition of the MO precursors should result in metal deposition, the thickness of which should be proportional to the MO-ion beam interaction time, while the residual volatile organics are concomitantly removed through vacuum pumping.

6.2.2. Evaluation of FIB Performance in Making Electrical Contacts to Nanomaterials

A major issue in FIB induced metal deposition is the sub-optimal electrical resistance of the deposited metals (e.g., in the case of platinum, gold, copper, cobalt, and tungsten), where electrical resistivity values have been reported to be orders of magnitude higher than that of the bulk metal. While it has been widely perceived, that contamination from the carbon of the precursors decreases the resistivity, it was shown, based on extensive investigations, that the resistance seems to be controlled by the implanted Ga+-metal from the MO playing a negligible role.

We focus on the electrical resistance of tungsten (W) and platinum (Pt) metal lines deposited in commercial FIB/SEM systems using Trimethyl(methylene)cyclopentadienyl) platinum: \(\text{C}_6\text{H}_5\text{Pt}\) and tungsten hexacarbonyl: \(\text{W} \text{(CO)}_6\), as the respective MO precursor gases. During the deposition, the ion beam accelerating voltage was fixed at a typical voltage of 30 kV, e.g., to minimize the contribution of the secondary electrons. Four commonly used metal deposition parameters were investigated, viz.,

(i) beam current—which defines the total Ga+ charge/unit time (in the range of 80 pA to 2.5 nA for Pt and 80 pA to 9.3 nA for W),

(ii) percentage of overlap between adjacent beam spots (in the range of 0% to 150%), with a positive value implying superposition and a negative value indicating the extent of spot separation,

(iii) defocus—a measure of the ion beam spread (in the range of 0 \(\mu\)m to 150 \(\mu\)m), with respect to the sample surface as a reference, and

(iv) temperature of the gas injection system (GIS), which regulates the MO vapor pressure (in the range of 42 °C to 54 °C for Pt and 41 °C to 62 °C for W).

Subsequent to depositing the W and Pt metal lines, the chemical composition of all the constituent elements was quantitatively analyzed through carefully following all the standard practices of energy dispersive spectroscopy (EDS). The EDS peak intensities of the W/Pt, Ga and O peaks, ratioed to the background intensity, were used to determine the elemental concentrations in the deposited metal lines using ZAF (Z: atomic number, A; absorption factor, F: fluorescence factor) based matrix corrections. The metal lines were contacted through Ti/Pd pads (patterned on plasma-enhanced chemical vapor deposited SiO coated Si substrate) for electrical measurements. The electrical resistivity (\(\rho\)) of the material was determined through four-probe measurements of the resistance (\(R\)) of the deposited metal lines (using a HP 34401A multimeter and a commercial probe station). The length (\(l\), along with

Figure 4. (picture courtesy Hasan Faraby, UC, San Diego) Focused Ion beam (FIB) based deposition is often used for depositing metal contacts and insulating films at the nanoscale. The deposition process involves heating a metalorganic (MO) precursor in a gas reservoir adjacent to a scanning electron microscope (SEM) chamber, subsequent to which MO vapor is controllably passed, through a gas nozzle, into the vacuum chamber. The vapor molecules adsorb onto the substrate and are decomposed through interaction with the ion beam, the extent of which should be proportional to the MO-ion beam interaction time, while the residual volatile organics are concomitantly removed through vacuum pumping.
adequately low to avoid sputtering effects associated with larger fluences at higher atomic % Ga. It was then concluded that Ga was the dominant factor in determining the electrical resistivity of the FIB deposited metal lines.

In order to better understand and model the electrical resistivity of the FIB deposited metal, the theoretical resistivity of the MO deposited metal-Ga-C composite was estimated through McLachlan’s general effective medium (GEM) based formulations. It was assumed that the mixture was constituted from two components—a low resistivity \( \rho_{lm} \) component (mainly from Ga with a resistivity of \( 27 \, \mu \Omega \cdot \text{cm} \)) and a high resistivity \( \rho_{h} \) component from C, un-decomposed MO precursor, etc. and that the variation observed in Figure 5(b) corresponded to a percolative transition, where increasing Ga through the FIB deposited metal line increased the overall electrical conductivity. The following form of the GEM was employed:

\[
\varphi \left[ \left( \rho_m \right)^{1/\varphi} - \left( \rho_0 \right)^{1/\varphi} \right] \\
\left[ \left( \rho_m \right)^{1/\varphi} + \left( \left( 1 - \varphi \right) / \varphi \right) \left( \rho_0 \right)^{1/\varphi} \right]^{1/\left( 1 - \varphi \right)} \\
+ \frac{\left( 1 - \varphi \right) \left( \rho_m \right)^{1/\varphi} - \left( \rho_0 \right)^{1/\varphi}}{\left( \rho_m \right)^{1/\varphi} + \left( \left( 1 - \varphi \right) / \varphi \right) \left( \rho_0 \right)^{1/\varphi}} = 0 \tag{5}
\]

In the above equation, \( \varphi \) is the atomic percentage of the low resistivity component (with \( \varphi \) being a critical atomic percentage of Ga at which a percolation path is formed through the medium) and \( t \) is a critical exponent. Equation (5) reduces to Bruggeman’s symmetric and asymmetric media equations in the appropriate limits of the resistivity and shape of the components, and can also be viewed as an electrical conductivity/resistivity percolation equation. For example, when \( \rho_m \to 0 \), Eq. (4) reduces to:

\[
\rho_m = \rho_0 \left( 1 - \varphi \right)^{-t/\varphi_c} \tag{6}
\]

Alternately, with \( \rho_m \to \infty \), Eq. (5) yields:

\[
\rho_m = \rho_0 \left( 1 - \varphi / \varphi_c \right)^{-t} \tag{7}
\]

Equation (5) may then be considered as a matched asymptotic expression between Eqs. (6) and (7) with \( \varphi_c \) being the matching asymptote.

Extrapolating the data from Figure 5(b) to zero atomic % Ga, the \( \rho_m \) was chosen to be \( 10^5 \, \mu \Omega \cdot \text{cm} \). We could not preclude Ga ion beams and solely use electron beam deposition to determine this value due to fundamental differences in the underlying mechanisms, e.g., ions have orders of magnitude higher mass and a smaller penetration depth compared to electrons. The values of \( \varphi_c \) were estimated separately, using Eqs. (6) and (7) for low and high values of \( \varphi \) and yielded \( \varphi_{c,2} \) and \( \varphi_{c,3} \), respectively. The difference \( \Delta \varphi_c = \left( \varphi_{c,2} - \varphi_{c,3} \right) \) was minimized through using an asymptotic \( \varphi_c = 0.05 \). Subsequently, Eq. (5) was solved numerically for \( \rho_m \) and superposed on the experimental data of Figure 5(b), with a \( t = 1.3 \). The sensitivity of \( \rho_m \) to the width \( w \) and the height \( h \) of the metal lines were estimated from EM imaging and FIB cross sectioning.

The estimated resistivity, \( \rho = Ru / l \) with respect to M (i.e., W or Pt) and Ga atomic % was plotted in Figure 5. Generally, the \( \rho \) relates to the decomposition product of the MO precursor while EDS (used for determining the atomic %) identifies elements independent of their chemical bonding state. Figure 5(a) does not seem to indicate any clear correlation of \( \rho \) with atomic % of M. For Pt (with bulk resistivity \( \approx 10.6 \, \mu \Omega \cdot \text{cm} \)) metal lines, the \( \rho \) was found to be in the range of \( 10^2 - 10^3 \, \mu \Omega \cdot \text{cm} \), with a metal concentration (as determined through EDS) in the range of 20% to 40%. For W metal (with concentrations between 30-40%) lines, the \( \rho \) was found to be smaller, in the range of 100-400 \( \mu \Omega \cdot \text{cm} \), while still larger than that of the bulk W (\( \approx 5.5 \, \mu \Omega \cdot \text{cm} \)). However, a clear correlation of decreasing \( \rho \) indicating increasingly metallic characteristics, with increasing Ga concentration was observed and is shown in Figure 5(b). The Ga content was kept...
a fitting parameter (say, $\alpha$) was defined through a ratio ($S_\alpha$) of the unit change in the composite medium resistivity to unit change in the $\alpha$, i.e.,

$$S_\alpha = \left( \frac{d\rho_m}{\rho_m} \right) \left( \frac{d\alpha}{\alpha} \right)$$ (8)

e.g., an $S_\alpha = 0.1$, implies that a unit change in $\alpha$ would yield a 0.1 unit change in the $\rho_m$. Equation (8) was evaluated, on the basis of Eq. (5), and plotted with respect to $\varphi$ in Figure 6, below.

It was noted that $\varphi_c$ could also be estimated from the maxima of the $S_{\varphi_c}$ and $S_t$, given that $\varphi_c$ determines the transition from the high to low resistivity behavior of the medium. Similarly, $S_{\rho_m}$ ~ 1 for $\varphi < \varphi_c$, implying a correspondence between $\rho_m$ and $\rho_{0_m}$, while for $\varphi > \varphi_c$ the correspondence is drastically reduced. A converse dependence was noted for the $S_{\rho_{0_m}}$ (indicating a match between $\rho_m$ and $\rho_{0_m}$), where the ratio tends to unity for $\varphi > \varphi_c$. The value of $\varphi$ at the intersection of $S_{\rho_m}$ and $S_{\rho_{0_m}}$ could then also be used to determine the $\varphi_c$.

In conclusion, it was shown that the concentration of Ga (the constituent in the ion beam) seems to be the dominant factor in determining the electrical resistance of FIB deposited lines of both metals and insulators. It was also observed that it was the chemical composition of the deposited material that determines the electrical resistivity and not the FIB beam parameters per se. The surprising aspect was that the intended metal from the decomposition of the MO precursor does not seem to strongly contribute, presumably due to incomplete precursor decomposition. It may be suggested that, given the limitations with precursor volatility and system stability, the deposition parameters that directly controls Ga$^+$ concentration should only be considered for tuning the resistivity of FIB metal depositions for depositing contacts or insulator layers on nanostructures.

7. SUMMARY

While it has been indicated that nanostructures exhibiting quantum mechanical characteristics would bring forth novel science and applications, the harness of unique properties demands optimal electrical contacts, which pass electrical current seamlessly to/from the material. However, it was seen that interfacing nano-objects to the 3-D world would imply a dimensional crossover. Consequently, there is a fundamental intrinsic resistance of the order of $h/e^2$ (~6.5 kΩ) due to the electrical carrier mode number mismatch between the contact and the nanostructure. While increasing the nanostructure size, increasing the number of modes, may reduce such a resistance, caution must be placed on the extent of increase while preserving quantum confinement effects of astonishing scientific and technological diversity and application. The additional influence of surface states in reducing the barrier to carrier motion at the contact-material interface as well as the influence of the ambient must also be considered given the large surface area to volume ratio inherent to such small scales. The ubiquitous presence of impurities, that seem to be even evident in the vacuum based methods of laying down the contacts, considerably affect electrical contacts to nanoscale materials which may then need to be revisited from a fundamental viewpoint.

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References and Notes


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