Chapter 5

Effect of Electrodes Material on Nanometer-Scale Electron Transport

5.1 Introduction

The emergent field of single molecule electronics is the basis for fabricating the electronic circuits with single molecules being the processing components. Currently, the focus is on discovering molecules with fascinating properties and on inventing means of finding reliable and reproducible contacts between the molecular components and the bulk material of the electrodes. The theory of single molecule devices is particularly motivating since the system under consideration is an open quantum system in non-equilibrium (driven by voltage). In the low bias voltage regime, the non-equilibrium nature of the molecular junctions can be ignored, and the current-voltage characteristics of the device can be calculated using the equilibrium electronic structure of the system. However, in stronger bias regimes a more sophisticated treatment is required, as there is no longer a variational principle. In the elastic tunneling regime (when the passing electron does not exchange energy with the system), we could employ Landauer formalism [1-3] to calculate the transmission and hence the current through the system as a function of the applied bias voltage. Kim and Arnold [4] have suggested innovative methodologies towards the theoretical study of the tunneling current. In their papers, C. Caroli et. al [5-8] has suggested the techniques for the direct calculation of the tunneling current at nanoscale. In the inelastic tunneling, a reliable formalism based on the non-equilibrium Green's functions of Leo Kadanoff and Gordon Baym [9-12], Schwinger [13] and independently by Leonid Keldysh [14] was put forth by Ned Wingreen and Yigal Meir [15]. This Meir-Wingreen formulation [16] has been employed to exceptional realization by the molecular electronics community to observe the more challenging as well as thought-provoking instances where the transient electron exchanges energy with the molecular system i.e. through electron-phonon coupling or electronic excitations. Cini [17] has suggested simplified theory and applications on time-dependent electron transport.

The study of various transport parameters of nanoscale junctions consisting of a molecular monolayer in contact with different metal electrodes is of great importance for the future use of such molecular junctions. The electronic properties of the devices at nanometer scale are sensitive to the microscopic configuration of all essential device constituents including the organic molecules as well as metal electrodes. Some interesting effects that include negative differential conductance [18], blockade and the Kondo effects on single molecules [19-20],
resonant tunneling as well as conductance quantization have been reported, through the diverse molecules whether belonging to inorganic crystals or organic family, stringed to different metallic electrodes. Most of the experimental as well as theoretical studies had demonstrated that metallic electrodes exhibit better transport features and hence offer a lot of desirable features over their non-metallic counterparts. Though many metallic electrodes could be employed as molecular junctions for nanometer scale electron transport, yet most of the previously done work with regard to electrodes has been concentrated only on gold electrodes, and very few instances of electron transport through other metallic electrodes has been cited. It is pertinent to take into consideration the metallic electrodes built on top of Palladium, Aluminium, Titanium, Nickel, Copper, platinum, Silver and Lithium also to predict the impact of such electrodes on overall electron transport through the molecular junctions consisting of numerous molecules stringed to these metallic electrodes.

5.2 Our Objective

To model and simulate the electron transport at nanometer-scale through the molecular junctions comprising of various metallic electrodes

The molecule considered for our modeling are:

I. Hydrogen stringed to various metallic electrodes viz. Gold, Lithium, Silver and Platinum using ab-initio DFT approach

II. Acetone stringed to various metallic electrodes viz. Gold, Silver, Palladium and Platinum as well as a non-metallic electrode carbon (graphite) using semi-empirical EHT approach

5.3 Our Approach & Simulation Work

Towards the realization of better understanding of the effect of the electrodes made up of different materials on the nanometer scale electron transport through these molecular junctions, we worked firstly with Hydrogen stringed to different metallic electrodes using ab-initio DFT approach. Next we selected an organic molecule Acetone stringed to metallic as well as non-metallic electrodes using semi-empirical EHT approach and elucidate the transport properties of such molecular junctions.

We modelled and proposed a metallic junction structure in order to realize the various transport characteristics through it by selecting various metallic electrodes viz. gold,
platinum, silver, lithium, palladium and a non-metallic carbon (graphite). The system we considered consists of three parts—the left electrode, scattering region and the right electrode. In our calculations, the region in the box indicates one electrode and the one between the two boxes is the central scattering region.

The geometrical optimizations and the electronic transport properties of the molecular junctions thus formed are calculated using first principles simulation package Atomistix Tool Kit (ATK 12.2.0), which supports the both ab-initio density function theory (DFT) and the semi-empirical Extended Hückel Theory (EHT) approach within the keldysh's non-equilibrium green function (NEGF) formalism. We obtained the current (I) - voltage (V) characteristics from the Landauer- Büttiker formalism [21-24] as follows:-

\[ I(V) = G_0 \int [f(E - \mu_L) - f(E - \mu_R)] \cdot T(E, V) \, dE \quad (5.1) \]

Where \( G_0 = \frac{2e^2}{h} \) is called the quantum conductance as suggested by Landauer, where ‘e’ is the electron charge and ‘h’ is plank’s constant.

\( f \) = Fermi function
\( \mu_L, \mu_R = \) Electrochemical potential of left and right electrode respectively
\( T(E,V) = \) Bias-dependent transmission probability

![Figure 5.1](image) Schematic plot of energy (vertical distance) vs. molecular distance (horizontal) for a metal-molecule-metal junction.

For the transport properties to be dominated by the molecule, the physical gap between the electrodes and the molecule \((x_1, x_3)\) must be much less than the width of the molecule \((x_2)\).
However these gaps must be big enough so that the interaction between the molecular states and the metal is small. Here the lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO) are related to the electron affinity ($E_A$) and ionization potential ($I_P$) as corrected for the energy distance between charged and uncharged states ($\Delta$). Current is carried by electrons at Fermi energy ($E_F$) located below the vacuum by an amount of the energy equal to the work function ($\Phi$).

5.4 Hydrogen stringed to different metallic electrodes using ab-initio DFT approach

To measure the impact of the different metallic electrodes on the nano-meter scale electron transport, we scrutinized the effect by binding the hydrogen molecule to various metallic electrodes using density function theory (DFT) approach. The computational model was selected as jellium model and geometry optimization was performed keeping in mind all the boundary conditions discussed in the above paragraph and as shown in the figure 6.1.

5.4.1 Our Model for Computation

As mentioned above, to account for the effect of the various metallic electrodes on the transport parameters of a molecule, we first started with a hydrogen molecule in the scattering region stringed to the various metallic electrodes as shown below. We incorporated ab-initio DFT approach while calculating the electron transport characteristics through the molecule under consideration.

![Figure 5.2 Hydrogen molecule alternatively stringed to Gold, Lithium, Silver and Platinum electrodes](image)
5.4.2 RESULTS AND DELIBERATIONS

The figures 5.3a exhibit the I-V characteristics for the said molecular junction under applied bias and we could see the negative differential resistance being exhibited between -0.4 V and 0.4 V. In figure 5.3b, we could see the $dI/dV$ curve peaking at 0 V with conductance becoming $58\mu S$ ($0.75 G_0$). The reason for this sudden rise at 0 V is lifting of the coulomb blockade and the emergence of resonant tunneling.

![I-V Curve](image)

![dl/dV-V Curve](image)

**Figure 5.3 I-V and dl/dV curves for Gold + Hydrogen combination**

In figure 5.4a, we see that the range of the current for the stipulated external bias voltages has increased up to 30 µA, but the curve has become linear for most bias voltage and a small NDR region is visualized only at -0.6 V and 0.6 V. The differential conductance $dI/dV$ becomes maximum $52.7 \mu S$ ($0.68 G_0$) at 0 V, which indicates kondo assisted resonant tunneling because of lifting of coulomb blockade.
Figure 5.4 I-V and dI/dV curves for Lithium + Hydrogen combination

The figure 5.5a demonstrated the increased region of negative differential resistance with silver electrodes with NDR observed between -1.2 V to 1.2 V. We observe the current to remain quantized at 0 ampere for the bias voltage between -2 V to -1.2 V, as well as between 1.2 V and 2 Volt. The poor transmission of current was on account of strong HOMO-LUMO band gap at these bias voltage ranges and hence quantization of charge at these bias voltages. Figure 5.5 b demonstrated lifting of coulomb blockade and resonant tunneling with maximum conductance of 28 μS (0.36 G_0). One more important phenomenon visible here is the quantization of the current between -1 V and -0.5 V as well as between 0.5 V and 1 V, which also scrutinizes the resonant tunneling. The current saturates at -8 μA between -1 V and -0.5 V before rising to become 8 μA and then again quantizing at that level.
Figure 5.5 I-V and dl/dV curves for Silver + Hydrogen combination

In figure 5.6 a, the NDR region was observed between -2 V to 2 V with maximum to minimum current ranging from around 30 µA to -30 µA with possible quantized current between -1.5 V and -0.5 V and 0.5 V and 1.5 V. These quantized states pointed towards heavy interaction at these levels and sudden rise of the current when the bias voltage was increased beyond this value. At low temperatures, most single molecule devices exhibit blockade with discrete conductance peaks that correspond to quantum excitations of the molecule. The origin of the observed quantum excitation varies from molecule to molecule depending on how tunneling electrons interact with various molecular degrees of freedom. Vibrational excitation is the one that is most frequently observed and expands the molecular
levels dramatically and reduces the HOMO-LUMO gap around zero bias, which leads to phenomenal tunneling.

The figure 5.6 b shows the $\text{dI/dV}$ characteristics with respect to the applied voltage and exhibits lifting of the blockade and kondo assisted tunneling with conduction reaching maximum value of $50 \, \mu\text{S} \left(0.65 \, G_0\right)$ at $0 \, \text{V}$. Two prominent valleys around $-1 \, \text{V}$ and $1 \, \text{V}$ indicate strong interaction as well as subsequent interplaying of the charges and hence lifting of the blockade.

![I-V Curve](image1)

![dI/dV-V Curve](image2)

**Figure 5.6 I-V and dI/dV curves for Platinum + Hydrogen combination**

The modeling of the non-linear features of the I-V curves at nanometer-scale is one of the important tools used to understand the dynamics of nano structures. It is because I-V curves demonstrate the effect of interaction, quantum interference, kondo effects, and the excitation of vibrational degrees of freedom etc. The observed results from our modeling and simulation approach showed that the molecular junctions of hydrogen with different metallic electrodes
(Au, Li, Ag & Pt) demonstrated very strong non-linearities in the I-V curves with huge negative differential conductance (NDC).

During the course of electromigration, the conductance remained below the conductance quantum $G_0 \left(\frac{2e^2}{h}\right)$, indicating a tunneling gap between the electrodes. As the voltage was increased further, there was a linear rise in the observed value of the current. This behaviour was altogether missing for bare metallic electrodes (Au, Li, Ag & Pt). Therefore, we interpret this jump because of the insertion of the hydrogen molecule between these metallic electrodes.

Another vital observation was a peak in $\frac{dI}{dV}$ at $V=0$ in all the cases. The reason we could cite for the observed phenomenon is kondo assisted tunneling and the lifting of the blockade. The maximum conductance values for gold, lithium, silver and platinum electrodes were observed to be $0.75G_0$, $0.68G_0$, $0.36G_0$ and $0.65G_0$ respectively. The observation of lower values of conductance than the quantum conductance $G_0$ indicated the weak coupling limit between the molecule and electrodes and hence exhibiting tunnel contacts. The visible dips in the conductance could be due to the interference in the resonant cavity. This showed the least interaction between the molecule in the scattering region with the metallic electrodes and the electron transport was thought to be two-step tunneling process contributing to kondo effect. The exhibited alternations and the higher peaks in $dI/dV$ curve marked the key signatures of the kondo effects.

All the instances of molecular junctions under observation comprising of various metallic electrodes, exhibited negative differential conductance (NDC) though the range of bias voltage, where this NDC was visible varied for each instance. The order of precedence of various metallic electrodes, where NDC was observed to be prominent, was platinum, silver, gold and lithium respectively.

5.5 Acetone stringed to various metallic electrodes viz. Gold, Silver, Palladium, Platinum and a non-metallic electrode carbon

In order to observe the impact of metallic electrodes on the electron transport through the organic molecules, we stringed acetone to the multiple metallic electrodes using extended Hückel theory. Though it is well understood that non-metallic electrodes exhibit, poor transmission properties when compared with their metallic counterparts, we selected one non-metal carbon as the material of the electrodes for further elucidation.
5.5.1 Modeling & Simulation

The overall schema for our modeling setup is based upon two-probe model consisting of left and right semi-infinite electrodes that emulate as source and drain of a conventional transistor and the scattering region constituting of the molecule acetone. In this case, we envisaged acetone molecule by connecting it to the various metallic electrodes (Au, Ag, Pt, Pd) one by
one and finally with a non-metallic graphite electrodes (figure 5.7) all having different chemical properties. Gold electrodes had been commonly used in single molecule junctions previously because of their stability in air. Both gold and platinum are highly non-reactive metals, while other metals like silver and palladium form their metal oxides which affect the conductance up to a large extent and offers large resistance to the transmission of current [15].

We scrutinized the conduction properties of acetone by coupling it to different metallic and non-metallic contacts. Various results have proved that metallic electrodes are better electrical contacts than non-metallic electrodes. Our objective for this research work was to compare the overall impact of metallic and non-metallic electrodes on nano meter scale electron transport through these molecular junctions and suggesting the optimal material of electrode to predict the transport properties of acetone stringed to different metallic electrodes -gold, silver, platinum and palladium and non-metallic graphite electrodes. We simulated I-V curves, transmission spectra and conductance curves at various applied bias ranging from -1V to 1V with each electrical contact.

5.5.2 Results and Cogitation

According to Landauer, the current through the junction occurs due to the elastic scattering of electrons between two electrodes. Thus the current calculated by the Landauer- Büttiker formalism [13-14] is given by

\[
I(V_b) = \frac{2e^2}{h} \int T(E, V_b) dE
\]

Where \(2e^2 / h\) is the quantum unit of conductance \((G_0)\), \(T(E, V_b)\) is the transmission function, 
\(\mu_L (V_b) = \mu_L (0) + eV_b/2\) and 
\(\mu_R (V_b) = \mu_R (0) + eV_b/2\) are the chemical potentials of the left/right electrodes, with \(\mu_{L,R} (0)\) being the average Fermi level of the system without bias and 
\(V_b = (\mu_L - \mu_R) / e\) being the bias voltage.

The maximum value of current was observed as 20.385 \(\mu A\) for gold which stepped down to 12.549 \(\mu A\) for platinum, whereas this value declined to 0.6 \(\mu A\) for palladium and broached to 0.15\(\mu A\) when the electrodes were changed to silver (figure 2). The most noticeable feature observed was the negative differential resistance (NDR) while working with platinum and palladium which motivated us to work further with these two metals, whereas silver showed tunnelling of electrons instead of conduction.
a) Platinum and palladium electrodes: Both platinum and palladium belong to the platinum group metals in the periodic table. The I-V curves in (Figure 5.8 (b)) clearly demonstrated that both these metal contacts show similar current transmission characteristics except variations in the amplitude of current transmitted. Both electric contacts exhibit negative differential resistance (NDR) in the range -1V to -0.5V and from 0.5V to 1V as the current decreased with increase in bias. The current - voltage characteristics are dependent largely on the molecule and the electrodes. The Fermi levels, current transmission and band lining up of electrons change on changing the material of 2 semi-infinite electrodes.

Figure 5.8: I-V Curves comparing a) metallic and non-metallic electrodes b) different metallic electrodes
b) Gold electrodes: Initially, the current increased with increase in bias, then with a slight negative differential resistance, the current again started increasing (figure 5.8 (b)). The linearity in I-V curve is observed till the current reaches value of 20.385μA. The maximum current transmission was observed with gold electrodes.

c) Silver electrodes: The NDR effect as witnessed with platinum and palladium is not seen while using silver electrodes instead tunnelling of electrons was observed where the current is ranging from -100 nA to 150 nA with bias voltages ranging from -1V to 1V (figure 5.8 (b)). Among metallic electrodes the least transmission of current is noticed with silver.

d) Non-metallic carbon electrodes: The current transmitted is least for the carbon electrodes of the order of 10^{-17} nA, thus indicating large potential barriers as the electrons didn't tunnel through due to large potential barriers (figure 5.8(a)).

To foster our experimental results, we agglomerated the clustered data for each electrode and reckoned the mean value of current for positive bias as 5655.524724 nA for gold electrodes, 3238.3978 nA with platinum which drops down to 150.4130 nA with palladium and further declines to 70.7930 nA with silver. So , mean value of current calculated for gold electrodes was 1.75 times the current transmitted using platinum, 37.60 times the current transmitted with palladium and 77.80 times the current transmitted using silver electrodes.

\[ I_{\text{mean}(\text{Au})} = 1.75 I_{\text{mean}(\text{Pt})} \]

\[ I_{\text{mean}(\text{Au})} = 37.60 I_{\text{mean}(\text{Pd})} \]

\[ I_{\text{mean}(\text{Au})} = 77.88 I_{\text{mean}(\text{Ag})} \]

The actual charge transfer is strongly dependent on the interaction of the molecule to the electrodes. Taking insight into the experimental as well as calculated results, we are competent to resolve that both gold and platinum contacts can form better junctions than Ag, Pd, C. No doubt quantitative explanation of the current-voltage characteristics has been made but it is very difficult to analyze the behaviour as small asymmetric binding can lead to large variations in the symmetric responses as suggested by Weber [19]. So, the geometry of molecule and their binding to the electrodes must be carefully analyzed before commencing the simulations.

According to Landauer, the total conductance of a ballistic constriction is equal to the quantized conductance \( G_0 (=2e^2/h) \) times the transmittance of all the Eigen channels present.
in the constriction, where the number of channels can be calculated by the chemical valence of the atom in the junction and the transmittance is proportional to the coupling between the atom and the electrode.

At -0.6 V and 0.6 V, gold electrodes depicted maximum value of conductance as 150μS which is 1.94\(G_0\), which suggested strong coupling between molecule and the gold contacts. Since \(G/G_0\) is greater than 1 for gold electrodes, so they act as metallic contacts supporting coherent electron transmission as explained by Landauer. During electro migration, conductance initially decreased below quantum conductance for small bias, thereby indicating blockade regime which resisted the current transmission and then conductance finally increased to a finite value around zero bias with gold electrodes. In this case, there is no accessible energy level within the tunnelling range of electrode. Blockade is observable when three conditions are met. Firstly, the bias voltage must be lower than the charge on the electron divided by the self-capacitance \(V_{\text{bias}}< e/C\). Secondy, the thermal energy \((k_B T)\) must be less than the charging energy \((E_C=e^2/2C)\), otherwise the electron will be able to jump through the tunnel junction. Third condition, derived by Heisenberg's Uncertainty Principle, states that tunnelling resistance must be greater than \(h/e^2\).

Platinum electrodes exhibited maximum conductance of 50μS which is 0.64 \(G_0\) (figure 5.9), whereas this value descended to 3μS (0.038\(G_0\)), when we changed the electrodes to palladium (figure 5.9). Both platinum and palladium showed negative differential conductance from -0.5 V to 0.5 V bias range. The maximum conductance recorded for silver was just 0.4μS (0.0051 \(G_0\)) at the same voltage (figure 3). The value of \(G/G_0<1\) in case of platinum, palladium and silver indicated weak coupling of acetone with these metallic contacts, so these electrodes are tunnelling contacts where electron transmission is non-coherent. Sharp resonance peaks occurring at -0.5V to 0.5 V was another noticeable feature observed with palladium and platinum contacts. There exists a crossover between the two prominent peaks indicating that an electron has managed to tunnel through the tunnelling gap. The single electron tunnelling and Kondo effects are also associated with the blockade regime i.e. weak coupling regime. With non-metallic electrodes the observed value of conductance is of the order of \(10^{-16}\) nS, thus elucidating that non-metallic electrodes showed least conductance and exhibited large tunnelling barriers.
In order to confirm our results, the conductance was scrutinized as a function of displacement current for each electrode (figure 5.10). The conductance initially increased from approximately 1.00E-04 S to 1.00E-05 S with gold electrodes, from 1.00E-06 to 1.00E-05 S with platinum electrodes, from 1.00E-07 to 1.00E-6 S for palladium electrodes, from 1.00E-07 to 1.00E-06 for silver electrodes. Here the maximum conductance of 0.4 $G_0$ was recorded with gold, 0.2 $G_0$ for platinum, while palladium and silver exhibited maximum conductance of 0.02 $G_0$ and 0.006 $G_0$ which again justifies our result that gold has more potential to be used as electrodes, than platinum, palladium and silver.

There are many factors that influence the conductance of the molecular junction such as bonding of the molecule to the contacts and the geometry of molecule that has been used in the central region. The electronic bonding of the molecule to the contacts alters the orbital energy levels of the molecule. Metallic contacts exhibit conductance of the order of $G_0$ or slightly less but when we changed the metallic electrodes to non-metallic, the calculated value of conductance is $8.0017 \times 10^{-17}$ of $G_0$. The computed value of conductance was maximal for gold, followed by platinum. The conductance dropped further for palladium and steeped down for silver and infinitesimal value of conductance was assimilated for carbon electrodes, making virtually impossible for these non-metallic electrodes to conduct. So these calculated results were found in conformance with our experimental results.
The conductance in single molecular junctions is proportional to transmission coefficient and is given by

\[ G = G_0 \cdot T(E_F) \]  \hspace{1cm} (5.3)

Where \( G_0 \) is quantum of conductance which is 77.27 μS and \( T(E_F) \) is the transmission coefficient at fermi energy. The resistance is calculated as inverse of conductance (\( R = 1/G \)) and is given by \( R = R_0 / T(E_F) \). These variegated values of resistance were plotted against applied bias (figure 5.11). The resistance offered by non-metallic electrodes to the transmission of current is very large as compared to other metallic electrodes (figure 5.11(a)). The flatness in curves for metallic contacts clearly demonstrates that metallic electrodes offers negligible resistance to the transmission of current as compared to non-metallic (carbon) electrodes.
When resistance curve was plotted for metallic electrodes to compare their transmission properties, we found that among metallic electrodes gold exhibited least resistance and silver exhibited largest values of resistance (figure 5.11 (b)).

The mean resistance was calculated at different applied biases for metallic and non-metallic electrodes separately. The calculated results revealed that carbon electrodes offered average resistance of $2.0097 \times 10^{18}$ mega ohms which looked massive when compared to the resistance offered by metallic electrodes. This substantial resistance offered by carbon electrodes made it virtually not possible to participate in electron transport by any mean. Among metallic contacts, gold exhibited an average resistance of 0.167 mega ohm whereas platinum offers a resistance of 1.202 mega ohm and this value increases to 8.0452 mega ohm for palladium and 9.7277 mega ohm for silver contacts. Such values revealed that gold formed better electrical contacts (metallic contacts) and hence exhibited strong coupling regime, when working with predicting the electron transport through acetone. The platinum electrodes exhibited strong to moderate coupling while the palladium and silver demonstrated weak coupling. The non-metallic carbon electrodes revealed the weakest coupling.

![Resistance Curve](image1)

![Resistance Curve](image2)

Figure 5.11 Resistance curve comparing a) metallic and non-metallic electrodes b) different metallic electrodes
5.6 Conclusion

We have developed a model of non-linear charge transport through metal-molecule-metal nanojunction. As we expected the transport to non-linear, we incorporated Keldysh's non-equilibrium green function (NEGF) formalism for our simulation and modeling approach. We have shown that interplay of the charging effects and spatially non-trivial electronic structure of the molecule can lead to kondo assisted tunneling in the form of current peaks as exhibited by conductance-voltage curves at zero bias, which signifies the lifting of the coulomb blockade. Another important revelation from the proposed work was the strong negative conductance (NDC) exhibited by all the metallic electrodes stringed to hydrogen molecule. NDC would be observed no matter whether the tunnel coupling of the lower or higher coupling is suppressed. We believe that the proposed model was fairly generic to be realized in certain cases of simple molecules with tunnel contacts to electrodes.

In nutshell, the escalating order of the transmission of current and conductance with different metallic (Au, Ag, Pt, Pd) and non-metallic contacts is: carbon < silver < palladium < platinum < gold. This order clearly delineated that non-metallic electrodes support minimum transmission of current as compared to metallic contacts. Among metallic electrodes, gold and platinum have great potential as choice for electrodes to be implemented in single molecule junctions. Moreover, the negative differential resistance observed while working with gold and platinum exemplified that both these metals could form good metallic contacts for implementation in nano scale structures.

Due to the large HOMO-LUMO gap, there is no available charge state (or its electrochemical potential) near the Fermi level of the electrodes. Therefore, the main conduction mechanism in this molecular junction is a direct electron tunneling between the source and drain electrodes. No doubt, large HOMO-LUMO gaps were observed while working with silver electrodes, and hence electron transport was supported through tunnelling of electrons rather than by normal conduction. The gold contacts supported coherent transmission through the molecule and thus behaved as metallic electrodes whereas silver, palladium, platinum electrons formed tunnelling contacts with all exhibiting conductance much less than the quantum conductance, i.e. $G < G_0$. Large variations in transport properties were observed due to difference in coupling of hydrogen ion to different metallic and non-metallic contacts. Though all mandatory precautions were taken to predict the quantum transport related phenomena, yet we accept that many explanations cited above may be still short of full understanding as it is still premature to explain the quantum mechanical treatment based on
modern quantum theory in details and many such doubts are open to debate among the research community [20].

References


