JOURNAL OF ALGEBRAIC STATISTICS
Volume 13, No. 2, 2022, p. 2060 - 2067
https://publishoa.com
ISSN: 1309-3452

The Conductance of Single - Electron Charging In Metallic Quantum Dots

Lamessa Gudata[1*], Arega Wakjira[1], Abel Saka[1]

[1]Dambi Dollo University, College of Natural and Computational Science, Department of Physics, Ethiopia.
lamessagudata21@gmail.com[1*], Arega Wakjira[1], aregawakjira17@gmail.com[1]

ABSTRACT

We have studied charging effect in a lateral split gate quantum dot defined by metal gates in the two dimensional electron gas of a GaAs structure. The gate structures allows an independent control of conductance's of the two tunnel barriers separating the quantum dot from the two dimensional leads, and enable us to vary number of m[that are located in the dot. We have measured coulomb blockade oscillations in the conductance as the function of gate voltage. Figures 1 – 3 are the results of the study. The conductance at high temperature is constant and at low temperature show oscillation both in positive and negative gate voltage. The current is carried by successive discrete charging and discharging of the dot, form single charge tunnelling.

Key Words: Conductance, Charging effect, Tunnelling, Quantum dots, Gate voltage

1. Introduction

The conductance of single electron charging effects have mostly studied in granular films, metal tunnel junctions, and scanning tunnelling microscopy grain junctions. More recently, it has become apparent that charging effects can strongly affect conductance properties of metallic submicron structures weakly coupled to contact leads by tunnel barriers. The conductance in the charging effect start to transport properties when both barriers conductance value of a point contact at $2e^2$/h. The study of quantum dots [1] continues to enjoy a high popularity. The conductance properties of nanostructures consisting of quantum dots [2]. The properties and functionalities of such structures strongly depend on the state of the leads, their coupling to the central region [3], the interactions of the electrons on the central region, and on external conditions like temperature. The experimental control of the relevant parameters and the theoretical understanding of their effect on measurable characteristics of devices are at the heart of their application potential.

Single electron charging belongings have mostly been studied in granular films, metal tunnel junctions [4]. More recently, it has become seeming that charging effects can strongly affect the transportation properties of metal submicron structures weakly coupled to the contact leads by tunnel barriers [5]. The study of charging effects in metal devices started with the observation of conductance oscillations in the quantum dots indicates that a lateral quantum dot with controllable potential barriers was used [6]. Their device could change the number of electrons in the dot one-by-one, which was seen in the conductance by the appearance of oscillations, and they confirmed the explanation in terms of charging effects [7]. In the quantum dots defined by split-gates in a two dimensional electron gas which shows geometry allows a detailed study of the conditions for observing charging effects, because of the ability to control the coupling of the quantum dot to the environment [8].

The name dot proposes an exceedingly small region of space. A metal quantum dot, however, is made out of roughly a million atoms with an equivalent number of electrons. Nearly all electrons are tightly bound to the nuclei of the material, though, and the number of free electrons in the dot can be very small [9]. The de Broglie wavelength of these electrons is comparable to the size of the dot, and the electrons occupy discrete quantum levels and have a discrete excitation spectrum [10]. The charging energy in the quantum dot is analogous to the ionization energy of an atom. This is the energy required to add or remove a single electron from the dot [11]. Because of the analogies to real atoms, quantum dots are sometimes referred to as artificial atoms [12]. The atom like physics of dots is studied not via their interaction with light, however, but instead by measuring their transport properties, that is, by their ability to carry an electric current [13]. Quantum dots are therefore artificial atoms with the intriguing possibility of attaching current and voltage leads to probe their atomic

JOURNAL OF ALGEBRAIC STATISTICS
Volume 13, No. 2, 2022, p. 2060 - 2067
https://publishoa.com
ISSN: 1309-3452
states. Single molecules as an active electronic unit have attracted huge attention both from the research community and industry [14]. Single molecules can offer several unique properties as an electronic unit. The size is within several nanometres for most simple molecules and hence the electronic spectrum is quantized with the typical energy scale of ~ eV [15]. They also allow self-assembly, which is very useful in fabricating electronic devices at such a small length scale [16]. Another huge advantage is their tremendous diversity and functionality. There exist an incredibly large number of chemicals and their different chemical and electrical functions can open up many new possibilities that have never been available [17].

We assume that the barrier at either contact is opaque enough that it serves as a tunnel barrier. Then an electron can be considered located either on the molecule or one of the electrodes. Electric current will flow when an electron can tunnel onto the molecule and subsequently off from it to the other electrode [18]. When a state is available between $S_\mu$and D_μ, the sequential tunnelling process can occur via this state while changing the number of electrons on the molecule between N and N+1. A large current will flow occur on state. In another way when there are no available states between $S_\mu$and D_μ, the current will be blocked and the number of electrons N on the molecule is fixed [19]. Only a small current will flow by a direct tunnelling between the two electrodes off" state. The on and off behaviour is caused by the quantized electronic structure of a molecule. This quantized structure can be attributed to the charge addition energy and the electronic excitation spectrum [20]. The model presented here assumes that the contacts are behaving as tunnel barriers. Even though some molecules can be connected to the leads without forming a tunnel barrier at the contacts [21], the single molecule devices described in this thesis forms tunnel contacts and their electrical conductance can be explained based on the sequential tunnelling process [22].

2. Methods and Materials

To discuss charging effects in quantum dots, we follow the recent works [23] in which the charging theory for metal systems [24] is generalized to include discrete energy states. At sufficiently large negative voltage applied to the quantum point contact, the induced potential barriers will strongly localize the electrons in the dot [25]. The number of electrons in the dot is therefore determined being an integer and can only be changed by an integer. The charging energy of the dot can be written as:

$$E_c = \frac{(-en + Q_0)^2}{2C} \qquad \text{Eq(1)}$$

Where n = N - N_0, $Q_0 = C_sV_s + C_dV_d + C_gV_g$ and C is the total capacitance of the quantum dots C = $C_s + C_d + C_g$. The integer part of the additional charge in the dot is en = e (N —N_0), where N is the number of electrons in the dot, and the basic charge e is taken positive. N_0 is the number of electrons at zero gate voltage and zero bias voltage ($N_0 > N$), which pays the positive background charge originating from the donors [26]. Q_0, represents the continuous part of the excess charge, which is induced by voltage differences V_s and $V_d$between the dot and the leads (eV_l = μ_l - $\mu_d(N), eV_r = \mu_d(N) - \mu_r$ where $\mu_d(N)$ *is* the electrochemical potential of the dot. If n = 1 and $Q_0 = 0$, gives the charging energy $\frac{e^2}{C}$ for a single electron. For our description, we take E_c= $\frac{e^2}{C}$ as the unit for charging energy. Moreover, at zero bias voltage and at fixed gate voltage, the induced charge Q_0 can be rewarded by tunnelling of as many electrons into or out of the dot as required to decrease the total charge to a value smaller than the elementary charge e, so the electrostatic energy is reduced to a value below $\frac{e^2}{C}$ [27]. In the experiment, we degree the conductance with a small bias voltage V = $\frac{\mu_l - \mu_r}{e}$ across the sample as the gate voltage are varied. Then, simplify $Q_0 = C_gV_g$ where V_g denotes the gate voltage, which is varied, and C_g the capacitance between this gate and the dot [28]. The ground state energy for N electrons in the dots at zero temperature is the sum over the single particle energies E_p relative to the bottom of the conduction band, and the electrostatic energy:

$$U(N) = \sum_{p=1}^{N} E_p + \frac{(-en + C_gV_g)^2}{2C} \qquad (2)$$

JOURNAL OF ALGEBRAIC STATISTICS
Volume 13, No. 2, 2022, p. 2060 - 2067
https://publishoa.com
ISSN: 1309-3452
From the above equation, the electrochemical potential which by definition is the minimum energy necessary to add the Nth electron to the dot:

$$\mu_d(\mathrm{N}) = \mathrm{U(N)} - \mathrm{U(N\text{-}1)} \tag{3}$$

We can rearrange Eq(3) to get:

$$\mu_d(\mathrm{N}) = E_N + \frac{(n-1/2)e^2}{C} - \mathrm{e}\frac{C_g}{C}V_g \tag{4}$$

When μ_d(N) = μ_{ch}(N) + eφ_N, the electrochemical potential is the sum of the chemical potential μ_d(N) = E_N and the electrostatic potential eφ_N. When the number of electrons is changed by one, so that the resulting change in electrochemical potential at fixed voltage is:

$$\mu_d(\mathrm{N+1}) - \mu_d(\mathrm{N}) = E_{N+1} - E_N + e^2/\mathrm{C} \tag{5}$$

Eq(5) implies that the electrochemical potential changes by a finite energy when an electron is added to the dot. μ_d(N + 1) - μ_d(N) is large for large energy splitting between consecutive 0D state and for small capacitance. This energy gap container leads to a blockade for tunnelling of electron into and out of the do. E_{N+1} electron cannot tunnel into the dot because the resulting electrochemical potential μ_d(N + 1) is higher than the electrochemical potentials of the reservoirs. Therefore, μ_d(N) < $\mu_l <$ μ_d(N + 1) the electron transport is blocked, which is known as the Coulomb blockade. Transport is only possible by thermal activation or tunneling via virtual states [28]. Note that the energy gap of (5) takes place at the Fermi energy, which determines the transport properties and the activation energy. Below μ_d(N) the energy states are separated by $E_{N+1} - E_N$ which in our case, are much smaller energy differences. The Coulomb blockade can be eliminated by changing the gate voltage Q_0, so that μ_d(N + 1) is lined up between μ_l *and* μ_r, μ_l > μ_d(N + 1) > μ_r. Therefore, an electron can tunnel from the left two dimensional electron gas reservoir into the dot μ_l > μ_d(N + 1). The electrochemical potential in the dot increases by the amount given in (5), which in our structure is dominated by the increase in electrostatic energy $e\varphi_{N+1} - e\varphi_N = \frac{e^2}{C}$. Because μ_d(N + 1) > μ_r electron can tunnel out the dot to the right two dimensional electron gas reservoir causing the electrochemical potential to drop to μ_d(N) . Now, a new electron can tunnel into the dot and repeat the cycle [29]. This process where current is carried by successive discrete charging and discharging of the dot, is known as single charge tunnelling [12]. Then conductance single – electron charging in the dot is given by the equation:

$$\mathrm{G} = \frac{e^2}{KT}\sum_{p=1}^{\infty}\sum_{p=1}^{\infty}\frac{\Gamma_p^l\Gamma_p^l}{\Gamma_p^l+\Gamma_p^l}P_{eq}(\mathrm{N})F_{eq}(E_p \mid N)(1 - \mathrm{f}(E_p + U(N) - U(N-1) - E_p) \qquad \mathrm{Eq(6)}$$

3. Result and Discussion

We have plotted the conductance versus gate voltage using Eq(6) the result show different characteristics of conductance at high and low temperature. In Fig.1. The conductance of the dot is shown as a function of gate voltage. The conductance does not show oscillation in both positive and negative gate voltage. The conductance's show depression in in the positive gate voltage this is good agreement with the previous report [30].

JOURNAL OF ALGEBRAIC STATISTICS
Volume 13, No. 2, 2022, p. 2060 - 2067
https://publishoa.com
ISSN: 1309-3452

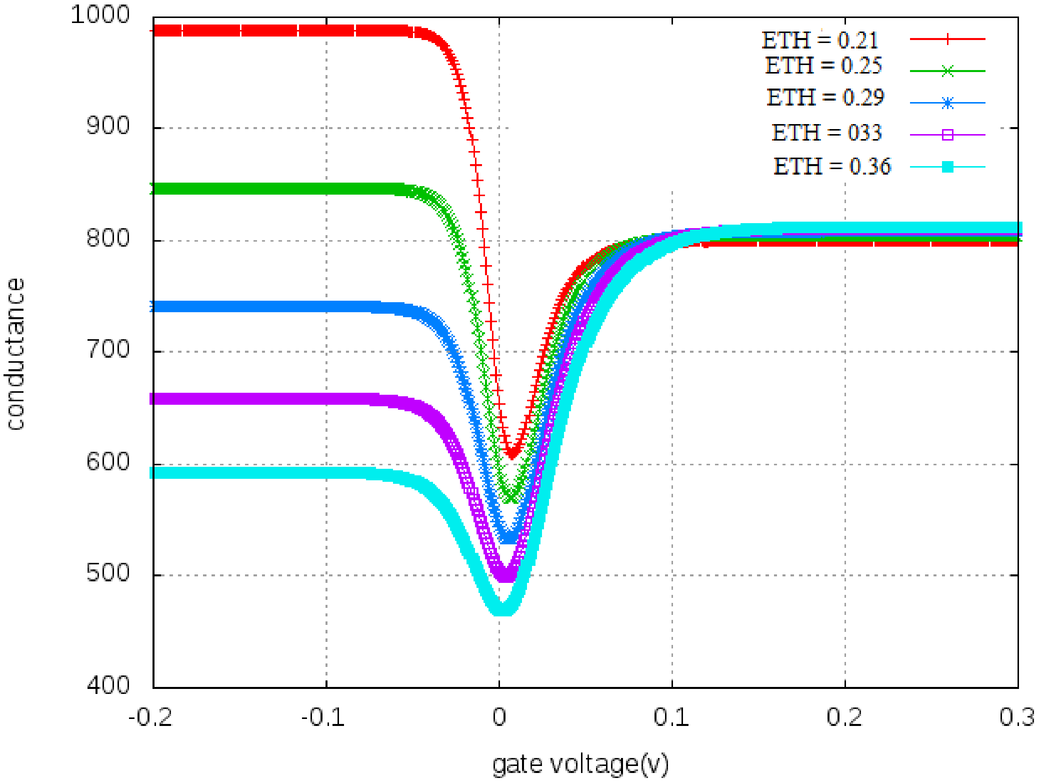

Figure1. The graph of conductance versus gate voltage $K_B\mathrm{T} \gg \Delta E$

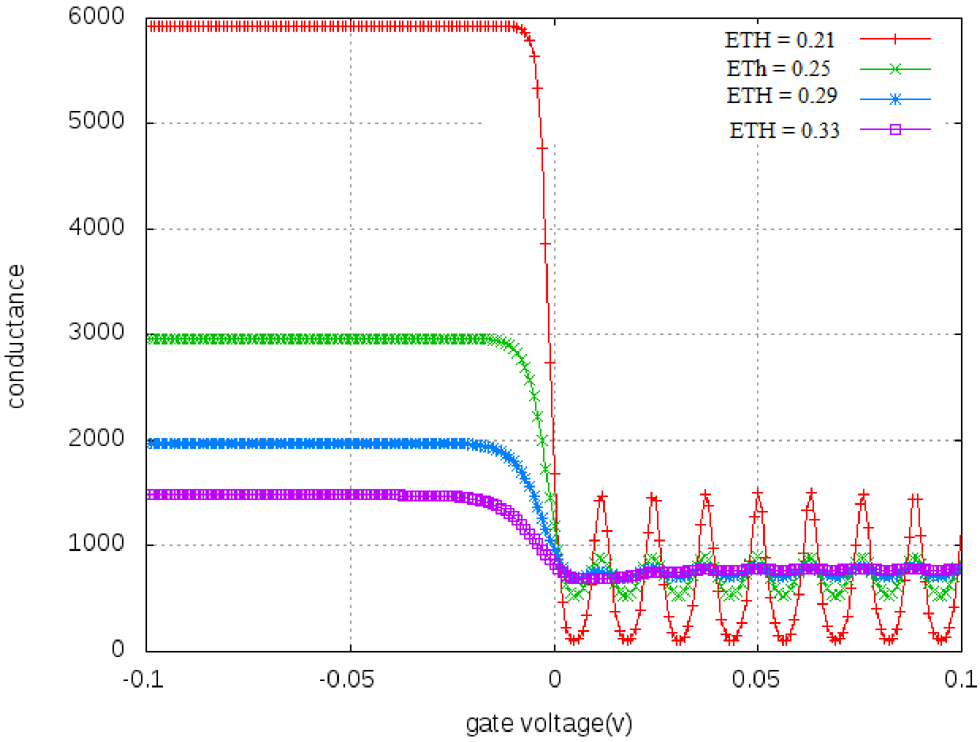

Figure 2, the graph of normalized conductance shows oscillations in the positive gate voltage.

JOURNAL OF ALGEBRAIC STATISTICS
Volume 13, No. 2, 2022, p. 2060 - 2067
https://publishoa.com
ISSN: 1309-3452

In figure 2. The conductance of the dot smoothly decreases as the gate voltage on the centre gate is decreased. This decrease is due to the influence of gate voltage on the conductance of the quantum point contact. Small oscillations appear in figure where the conductance of quantum point contact is quantized value. The amplitude of the oscillations increases at low temperature that is the result agreed with the previous report [31]. The oscillations are seen to disappear when the average dot conductance becomes too small.

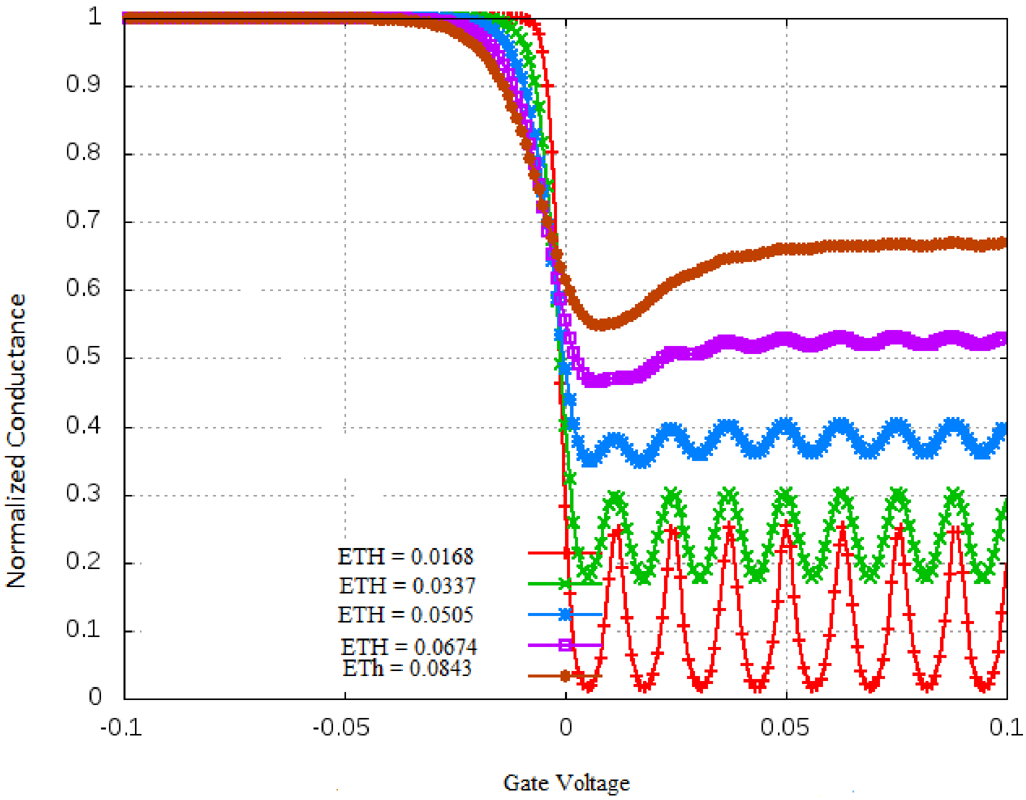

Figure3. The graph of normalized conductance at high and low temperature behaviour.

Figure 3. Show the normalized conductance at high and low temperature behaviour. The conductance show oscillations at low temperature and conductance is constant as temperature increased. Now, the oscillations appear as sharp peaks with amplitude up to $\frac{e^2}{c}$ and result is good agreement with the previous report [32]. Importantly, the maximum of the oscillations is considerably larger at lower temperature, indicating that the transmission through the dot is of a coherent resonant nature. Resonant transmission is a signature of tunnelling through a particular 0D energy state. Generally we have measured the oscillations by varying the voltage on the different gates, while keeping the voltage on the remaining gates fixed.

Conclusions

The charging effects in quantum dots, the charging theory for metal systems are generalized to discrete energy states. At sufficiently large negative voltage applied to the quantum point contact, the induced potential barriers will strongly localize the electrons in the dot. The number of electrons in the dot is therefore determined being an integer and can only be changed by an integer. The plotted conductance versus gate voltage using Eq(6) the result show different characteristics of conductance at high and low temperature. In Fig. 1 – 3 are the results of the study. We conclude that the theory of the conductance in single – electron charging effect good agreement with the experimental result of the study.

Reference

[1] Kleshch, V.I., Porshyn, V., Orekhov, A.S., Orekhov, A.S., Lützenkirchen-Hecht, D. and Obraztsov, A.N., 2021. Carbon single-electron point source controlled by Coulomb blockade. *Carbon*, *171*, pp.154-160.

[2] Sajjan, M., Hemmatiyan, S. and Mazziotti, D.A., 2021. Conductance Switching in an Organometallic Single-Electron Transistor Using Current-Constrained Reduced-Density Matrix Theory. *The Journal of Physical Chemistry A*.

[3] Khan, A., Iftikhar, M. and Abbas, S.M., 2021. Application of quantum dots in electronics. In *Green Sustainable Process for Chemical and Environmental Engineering and Science* (pp. 319-336). Elsevier.

[4] Shimada, H., Koike, T., Kikkawa, K., Konno, H., Ito, N., Kobayashi, R., Mizugaki, Y., Kanomata, K., Miura, M. and Hirose, F., 2021. Nanoscale Tunnel Junctions and Metallic Single-Electron Transistors via Shadow Evaporation and In Situ Atomic Layer Deposition of Tunnel Barriers. *ACS Applied Nano Materials*, *4*(2), pp.1401-1410.

[5] Shimada, H., Koike, T., Kikkawa, K., Konno, H., Ito, N., Kobayashi, R., Mizugaki, Y., Kanomata, K., Miura, M. and Hirose, F., 2021. Nanoscale Tunnel Junctions and Metallic Single-Electron Transistors via Shadow Evaporation and In Situ Atomic Layer Deposition of Tunnel Barriers. *ACS Applied Nano Materials*, *4*(2), pp.1401-1410.

[6] Qiu, T., Yang, L., Xiang, Y., Ye, Y., Zou, G., Hou, H. and Ji, X., 2021. Heterogeneous Interface Design for Enhanced Sodium Storage: Sb Quantum Dots Confined by Functional Carbon. *Small Methods*, p.2100188.

[7] Hong, Y., Ramanayaka, A.N., Stein, R., Stewart, M.D. and Pomeroy, J.M., 2021. Developing single-layer metal-oxide-semiconductor quantum dots for diagnostic qubits. *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena*, *39*(1), p.012204.

[8] Banszerus, L., Rothstein, A., Icking, E., Möller, S., Watanabe, K., Taniguchi, T., Stampfer, C. and Volk, C., 2021. Tunable interdot coupling in few-electron bilayer graphene double quantum dots. *Applied Physics Letters*, *118*(10), p.103101.

[9] Basu, T.S., Wakayama, Y. and Hayakawa, R., 2021. Theoretical Insight into Quantum Transport Via Molecular Dots in a Vertical Tunnel Transistor. *ACS Applied Electronic Materials*, *3*(2), pp.973-978.

[10] Connors, E.J., Nelson, J.J. and Nichol, J.M., 2021. Charge-noise spectroscopy of Si/SiGe quantum dots via dynamically-decoupled exchange oscillations. *arXiv preprint arXiv:2103.02448*.

[11] Ali, M., Riaz, R., Anjum, A.S., Sun, K.C., Li, H., Ahn, S., Jeong, S.H. and Ko, M.J., 2021. Microwave-assisted ultrafast in-situ growth of N-doped carbon quantum dots on multiwalled carbon nanotubes as an efficient electrocatalyst for photovoltaics. *Journal of Colloid and Interface Science*, *586*, pp.349-361.

[12] Rasal, A.S., Yadav, S., Yadav, A., Kashale, A.A., Manjunatha, S.T., Altaee, A. and Chang, J.Y., 2021. Carbon quantum dots for energy applications: a review. *ACS Applied Nano Materials*, *4*(7), pp.6515-6541.

[13] Hong, Y., Ramanayaka, A.N., Stein, R., Stewart, M.D. and Pomeroy, J.M., 2021. Developing single-layer metal-oxide-semiconductor quantum dots for diagnostic qubits. *Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena*, *39*(1), p.012204.

[14] McJunkin, T., MacQuarrie, E.R., Tom, L., Neyens, S.F., Dodson, J.P., Thorgrimsson, B., Corrigan, J., Ercan, H.E., Savage, D.E., Lagally, M.G. and Joynt, R., 2021. Valley splittings in Si/SiGe quantum dots with a germanium spike in the silicon well. *arXiv preprint arXiv:2104.08232*.

[15] Huang, J.Y., Lim, W.H., Leon, R.C., Yang, C.H., Hudson, F.E., Escott, C.C., Saraiva, A., Dzurak, A.S. and Laucht, A., 2021. A High-Sensitivity Charge Sensor for Silicon Qubits above 1 K. *Nano Letters*.

[16] Chen, E.H., Raach, K., Pan, A., Kiselev, A.A., Acuna, E., Blumoff, J.Z., Brecht, T., Choi, M.D., Ha, W., Hulbert, D.R. and Jura, M.P., 2021. Detuning Axis Pulsed Spectroscopy of Valley-Orbital States in Si/Si-Ge Quantum Dots. *Physical Review Applied*, *15*(4), p.044033.

[17] Zheng, S., Qin, F., Hu, C., Zhang, C., Ma, Y., Yang, R., Wei, L. and Bao, L., 2021. Up-converted nitrogen-doped carbon quantum dots to accelerate charge transfer of dibismuth tetraoxide for enhanced full-spectrum photocatalytic activity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *615*, p.126217.

[18] Kanne, T., Marnauza, M., Olsteins, D., Carrad, D.J., Sestoft, J.E., de Bruijckere, J., Zeng, L., Johnson, E., Olsson, E., Grove-Rasmussen, K. and Nygård, J., 2021. Epitaxial Pb on InAs nanowires for quantum devices. *Nature Nanotechnology*, pp.1-6.

[19] Kumbhakar, P., Karmakar, A.R., Das, G.P., Chakraborty, J., Tiwary, C.S. and Kumbhakar, P., 2021. Reversible temperature-dependent photoluminescence in semiconductor quantum dots for the development of a smartphone-based optical thermometer. *Nanoscale*, *13*(5), pp.2946-2954.

[20] Shimada, H., Koike, T., Kikkawa, K., Konno, H., Ito, N., Kobayashi, R., Mizugaki, Y., Kanomata, K., Miura, M. and Hirose, F., 2021. Nanoscale Tunnel Junctions and Metallic Single-Electron Transistors via Shadow Evaporation and In Situ Atomic Layer Deposition of Tunnel Barriers. *ACS Applied Nano Materials*, *4*(2), pp.1401-1410.

[21] Thomas, F.S., Nilsson, M., Ciaccia, C., Jünger, C., Rossi, F., Zannier, V., Sorba, L., Baumgartner, A. and Schönenberger, C., 2021. Spectroscopy of the local density-of-states in nanowires using integrated quantum dots. *arXiv preprint arXiv:2105.10910*.

[22] Mortemousque, P.A., Jadot, B., Chanrion, E., Thiney, V., Bäuerle, C., Ludwig, A., Wieck, A.D., Urdampilleta, M. and Meunier, T., 2021. Enhanced spin coherence while displacing electron in a 2D array of quantum dots. *arXiv preprint arXiv:2101.05968*.

[23] Tong, B., Wei, W., Wu, Z., Zhao, L., Ye, W., Wang, J., Chen, W., Soutis, C. and Mi, L., 2021. Interface Engineering Based on Multinanoscale Heterojunctions between NiO Quantum Dots, N-Doped Amorphous Carbon and Ni for Advanced Supercapacitor. *ACS Applied Energy Materials*, *4*(4), pp.3221-3230.

[24] Du, Z., Chen, M., Yin, F., Jiang, H., Wang, J. and Tang, J., 2021. Synergistic combination of TiO2-sol interconnecting-modified photoanode with alginate hydrogel-assisted electrolyte for quantum dots sensitized solar cells. *Solar Energy*, *215*, pp.189-197.

[25] Banszerus, L., Hecker, K., Icking, E., Trellenkamp, S., Lentz, F., Neumaier, D., Watanabe, K., Taniguchi, T., Volk, C. and Stampfer, C., 2021. Pulsed-gate spectroscopy of single-electron spin states in bilayer graphene quantum dots. *Physical Review B*, *103*(8), p.L081404.

[26] Kleshch, V.I., Porshyn, V., Orekhov, A.S., Orekhov, A.S., Lützenkirchen-Hecht, D. and Obraztsov, A.N., 2021. Carbon single-electron point source controlled by Coulomb blockade. *Carbon*, *171*, pp.154-160.

[27] McJunkin, T., MacQuarrie, E.R., Tom, L., Neyens, S.F., Dodson, J.P., Thorgrimsson, B., Corrigan, J., Ercan, H.E., Savage, D.E., Lagally, M.G. and Joynt, R., 2021. Valley splittings in Si/SiGe quantum dots with a germanium spike in the silicon well. *arXiv preprint arXiv:2104.08232*.

[28] Van Riggelen, F., Hendrickx, N.W., Lawrie, W.I.L., Russ, M., Sammak, A., Scappucci, G. and Veldhorst, M., 2021. A two-dimensional array of single-hole quantum dots. *Applied Physics Letters*, *118*(4), p.044002.

[29] Reifert, D., Kokainis, M., Ambainis, A., Kashcheyevs, V. and Ubbelohde, N., 2021. A random-walk benchmark for single-electron circuits. *Nature communications*, *12*(1), pp.1-7.

[30] Brange, F., Schmidt, A., Bayer, J.C., Wagner, T., Flindt, C. and Haug, R.J., 2021. Controlled emission time statistics of a dynamic single-electron transistor. *Science advances*, *7*(2), p.eabe0793.

JOURNAL OF ALGEBRAIC STATISTICS
Volume 13, No. 2, 2022, p. 2060 - 2067
https://publishoa.com
ISSN: 1309-3452
[31] Ercan, H.E., Friesen, M. and Coppersmith, S.N., 2021. Charge-noise resilience of two-electron quantum dots in Si/SiGe heterostructures. *arXiv preprint arXiv:2105.10643*.

[32] Sajjan, M., Hemmatiyan, S. and Mazziotti, D.A., 2021. Conductance Switching in an Organometallic Single-Electron Transistor Using Current-Constrained Reduced-Density Matrix Theory. *The Journal of Physical Chemistry A*.