Appl. Sci. Converg. Technol. 26(3): 50-51 (2017)
http://dx.doi.org/10.5757/ASCT.2017.26.3.50

Research Paper

Coulomb Interaction Induced Gap in an Al/SiO$_2$/Si:P tunnelling Device

Yongcheol Jo, Jongmin Kim, Sangeun Cho, Hyungsang Kim, and Hyunsik Im*
Division of Physics and Semiconductor Science, Dongguk University, Seoul, Korea

Received March 28, 2017; revised April 29, 2017; accepted April 30, 2017

Abstract Strongly correlated electron systems which induce strong electron-electron interaction at ultra-low temperatures have always been an intriguing topic in mesoscopic condensed matter physics. Below 130 mK, a peculiar gap can be found in Al/SiO$_2$/Si:P structured tunnelling devices. The gap survives at the base temperature of more than 1800 gauss (30 mK), contrary to the superconductivity of the top Al electrode, which is completely suppressed above 100 gauss. This outcome implies that the observed gap is induced by Coulomb interaction in the heavily doped Si.

Keywords: Coulomb interaction induced gap, Phosphorus doped silicon, Tunnelling device

I. Introduction

Silicon is like to be the best known semiconductor material. Despite its poor mobility and carrier concentration, it has been extensively used in the semiconductor industry owing to its simple doping processes and price advantage. Specially, doping increases the carrier density in the silicon, causing several intriguing phenomena, such as a semiconductor (insulator) to metal transition (MIT) [1]. As the temperature decreases, interactions caused by the increased carrier density are no longer negligible. Such behavior is not only useful from an industrial point of view but also presents an interesting topic in condensed matter physics.

In this work, we utilize tunnelling spectroscopy measurements at ultra-low temperature in an effort to investigate intriguing phenomena such as an abnormal gap induced by Coulomb interaction. We used a tunnelling device with a heavily doped Si:P and superconducting Al electrode.

II. Experiments

Al electrodes and the thermally grown SiO$_2$ tunnelling barrier used here were fabricated on phosphorus-doped silicon (Si:P) substrates (see Fig. 1(a)). The doping concentration of the Si:P exceeds $10^{19}/\mathrm{cm}^3$ in all cases. A native oxide layer on Si:P was removed using HF and the SiO$_2$ tunnelling barrier was directly grown on the Si:P using a tube furnace. A shadow mask was used to fabricate the Al electrodes with a thermal evaporator. Each electrode was 200 nm thick and had a diameter of 500 µm.

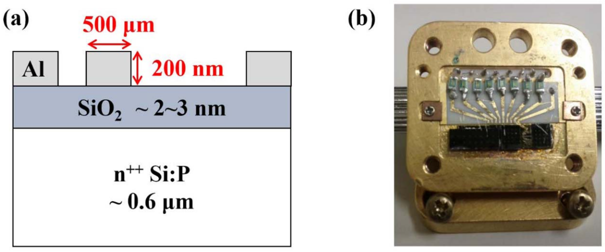

Figure 1. (a) Schematic of an Al/SiO$_2$/Si:P tunnelling device. (b) Mounted samples on the sample holder of a ^{3}He/^{4}He dilution system.

Ultra-low temperature transport characteristics were investigated using a ^{3}He/^{4}He dilution system. Figure 1(b) shows mounted samples on the holder. Silver paste was used to fix the sample, and a ground pad was connected. In addition, 25 µm Au wires were carefully bonded using a bonding machine. Special care was taken to avoid damage to the SiO$_2$ tunnelling layer. Up to 1800 gauss was applied using a superconducting magnet at a base temperature of 30 mK. All transport measurements were done at NEC in the Tsukuba Lab in Japan.

Tunnelling spectroscopy was conducted in order to observe the tunnelling DOS near the Fermi level of Si:P. This measurement allows us to investigate many condensed matter phenomena by measuring the DOS directly. The first-order derivative of the tunnelling current is proportional to the DOS [2]. The tunnelling current is given by the equation below:

$$I \propto \int_0^{eV} DOS_{Si}(E_f - eV + E)DOS_{Al}(E_f + E)dE\,. \qquad (1)$$

Because the Al electrode has a superconducting gap of approximately 0.2 mV, the tunnelling conductance between the superconducting gap of Al is directly proportional to

---

*Corresponding author
E-mail: hyunsik7@dongguk.edu

the tunnelling DOS of the Si:P. Thus, Eq. (1) becomes

$$dI/dV \propto DOS_{Si}(E_f - eV)\,. \tag{2}$$

This can also be applied to other metals which have a flat DOS structure in the vicinity of the Fermi level.

III. Results and Discussion

The temperature-dependent conductance curves of the sample are shown in Fig. 2(a). In this case, the well-known superconducting gap of the Al electrode was observed below 1.1 K, as expected (marked with arrows). As the temperature was decreased to less than 130 mK, another gap started to develop in the vicinity of the zero bias conductance. The observed gap survived at more than 1800 gauss, whereas the superconducting gap was completely suppressed above 100 gauss, as shown in Fig. 2(b). The observed conductance characteristics imply that the observed gap is independent of the applied magnetic fields.

Figure 3(a) shows the conductance curve (*dI/dV*) versus $V^{0.5}$. The relationship between the conductance and the bias voltage is well described by the typical tunnelling conductance behavio~~ur~~ for a Coulomb gap, as follows [3-6],

$$\sigma(V) \propto V^{0.5},$$

which is caused by long-range Coulomb interactions in disordered metals. This observation suggests that Si:P can be regarded as a disordered metal [4-6].

A Coulomb gap in the metallic region of a doped semiconductor leads to variable-range hopping (VRH) conductivity. Therefore, the temperature-induced smearing of the Coulomb gap can be determined by the following equation [5–7]:

$$\sigma(V = 0, T) \propto exp[-(T_0/T)^{0.5}]\,.$$

This formula is fundamentally in good agreement with our data (see Fig. 3(b)). As the temperature decreases from ~ 130 mK, the zero bias conductance decreases following the $T^{0.5}$ behaviour (see Fig. 3(b)), suggesting that the Coulomb gap appears below 130 mK. This is consistent with the data in Fig. 2(a).

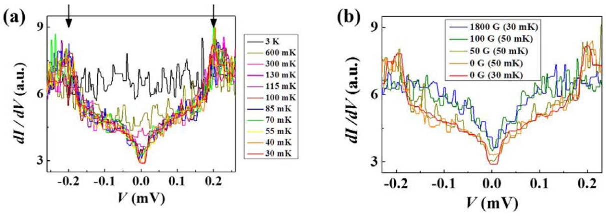

Figure 2. (a) Temperature and (b) magnetic field dependences of the tunnelling conductance in an Al/SiO$_2$/Si:P tunnelling device.

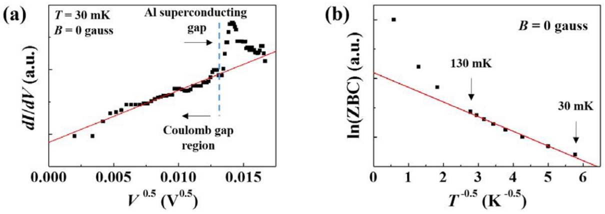

Figure 3. (a) Comparison of the measured conductance versus $V^{0.5}$ in an Al/SiO$_2$/Si:P device. The tunnelling conductance is symmetric with respect to the bias origin. (b) Logarithm of the zero bias conductance (ZBC) versus the inverse square root of the temperature. The line is a guide for the eye.

IV. Conclusions

A Al/SiO$_2$/Si:P tunnelling device was prepared by means of thermal annealing and evaporating techniques. An intriguing gap was found at highly phosphorus-doped Si below ~ 130 mK via tunnelling spectroscopy. The results from temperature- and magnetic-field-dependent conductance measurements showed that the observed gap is induced by long-range coulomb interaction between localized states. Phosphorus-doped silicon has been studied for decades only near the metal-insulator transition boundary. Our findings in the totally degenerated region suggest the possibility for additional discoveries beyond the boundary of MIT in Si:P.

Acknowledgements

This project was supported by the National Research Foundation (NRF) of Korea (Grant Nos. 2015R1A2A 2A01004782 and 2016R1A6A1A03012877).

References

[1] T.F. Rosenbaum, R.F. Milligan, M.A. Paalanen, G.A. Thomas, R.N. Bhatt, and W. Lin, Phys. Rev. B 27, 7509 (1983).
[2] C.J. Chen, *Introduction to Scanning Tunneling Microscopy* (Oxford University Press, New York, 1993).
[3] B.L. Althsuler and A.G. Aronov, Solid State Commun. 30, 115 (1979).
[4] M. Lee, J.G. Massey, V.L. Nguyen, and B.I. Shklovskii, Phys. Rev. B 60, 1582 (1999).
[5] A.L. Efros and B.I. Shklovskii, J. Phys. C 8, L49 (1975).
[6] B.I. Shklovskii and A.L. Efros, *Electronic Properties of Doped Semiconductors* (Springer, New York, 1984).
[7] I. Shlimak, M. Kaveh, R. Ussyshkin, V. Ginodman, S.D. Baranovskii, P. Thomas, H. Vaupel, and R.W. Van Der Heijden, Phys. Rev. Lett. 75, 4764 (1995).