DC Josephson current through the nanographite ribbon junctions

Katsunori Wakabayashi [a,1]

[a] *Department of Quantum Matter Science, Graduate School of Advanced Sciences of Matter (ADSM), Hiroshima University, Higashi-Hiroshima 739-8526, Japan*

Abstract

The DC Josephson current through a nano-graphite ribbon sandwiched between two conventional superconductors is theoretically studied by using the thermal Green function techniques based on the tight binding model. The electronic states of nano-graphite ribbons strongly depend on their shapes of edges, hence the behavior of the DC Josephson current crucially depends on the network topology of nano-graphite ribbons.

Key words: Josephson junction; nanographite; Green function method

Carbon based nano-scale materials such as fullerenes, carbon nanotues and nanographites are attracting the much attention due to their novel electronic properties. Nanographite is a nanometer-sized graphite systems which is situated between aromatic molecules and bulk graphite. In this system, the geometry of the carbon network is quite decisive for the electronic and magnetic properties[1]. Recently it has became possible to fabricate the hybrid systems of carbon nanotube and superconductor, and measure the electronic transport properties of these devices[2]. This progress of experiments opened a door to the application of the nanosized-carbon materials to the electronic devices. In this manuscript, we study the DC Josephson current through the nanographite ribbons sandwiched between two s-wave superconductors.

One of the models to describe the electronic properties of nano-graphites is graphite ribbon model[3]. Fig.1 is the schematic of the Josephson junction which sandwich (a) an armchair ribbon and (b) a zigzag ribbon between two superconductors. We define the length of the junction, L, by the number of the carbon slices. The width of the graphite ribbons, N, is defined by the number of atomic sites forming a single carbon slice, same as in the ref.[3]. The attached superconducting lead lines are semi-infinite system, where we use the nearest-neighbor tight-binding model of square lattice with conventional superconducting order parameter[4]. The DC Josephson current is calculated by

$$\begin{aligned} J &= -\frac{iet}{\hbar}\sum_{\sigma}\sum_{k=1}^{n_y}\langle c^{\dagger}_{j,k,\sigma}c_{j+1,k,\sigma} - \text{h.c}\rangle \\ &= \frac{iet}{\beta\hbar}\sum_{\omega_n}\sum_{k=1}^{n_y}\mathrm{Tr}\left[G_{\omega_n}(j,k;j+1,k) - G_{\omega_n}(j+1,k;j,k)\right], \end{aligned} \tag{1}$$

where the $\langle\cdots\rangle$ means thermal average, $\beta = 1/k_BT$, n_y is the number of the legs in the semi-infinite superconducting lead, and t is the transfer integral of the nearest-neighbor tight binding model. $G_{\omega_n}(j,k;j,k)$ is the Nambu Green's function with the Matsubara frequencies $\omega_n = \pi k_BT(2n+1)$. In Eq.(1), the summation on the ω_n is taken from $n = -\infty$ to $n = \infty$. The other notations follow the ref.[4]. We also use the recursive Green's function method.

Here we briefly summarize the electronic properties of nanographite ribbons. Armchair ribbons show metallic or semi-conducting behavior, depending on the ribbon width. Armchair ribbons of $N = 3m-1 \quad (m = 1, 2, 3, \cdots)$ are metallic, otherwise semiconducting. The metallic armchair ribbons have the linear dispersion at the low-lying energies[3]. On the

[1] E-mail: waka@qp.hiroshima-u.ac.jp

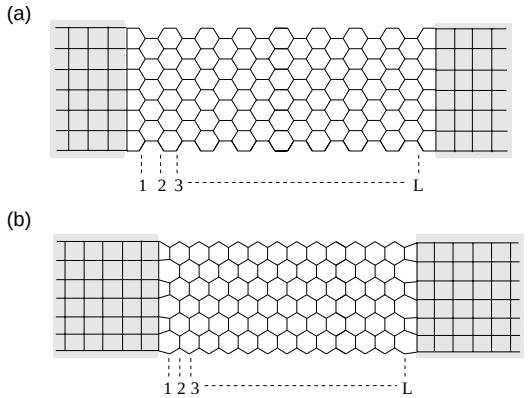

Fig. 1. The schematic of the Josephson junctions which sandwich a (a) armchair ribbon and (b) zigzag ribbon, where the shaded square ladder lattice is the semiinfinite superconducting lead line. The length of the junction is defined by the number of carbon slices.

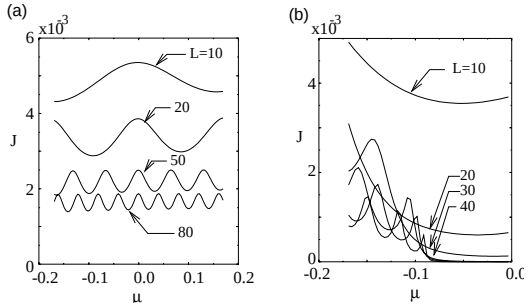

Fig. 2. The chemical potential dependence of the DC Josephson current through the armchair ribbon of (a) $N = 20$ (metallic) and (b) $N = 21$ (semi-conducting), where $1/\beta = 0.0001$

other hand, Zigzag ribbons show the metallic behavior for arbitrary width. In addition, zigzag ribbons show the peculiar energy dispersion of $E \sim k^N$ around the $E = 0$. This energy dispersion introduces in the sharp peak in the density of the states. Thus the electronic states of nanographites crucially depend on their edge structures.

In Fig. 2(a), we show the chemical potential dependence of the DC Josephson current through the metallic armchair ribbons($N = 20$), where $\beta = 0.0001$. Here we use the transfer integral (t) as the unit of energy, and the unit of the current is $et/\beta\hbar$. The length of the junction gets longer, the magnitude of the current gradually decreases. We have also checked that at the higher temperature region of $k_BT > \Delta E$, the Josephson currents show the exponential decay to the junction length, $\exp(-L/\xi_c)$. Here ΔE is a energy space between the Andreev bound states formed in the nanographites, and ξ_c is the correlation length in the clean limit. At lower temperatures, the currents depends on $(1/L)\exp(-L/\xi_c)$. These behaviors coincide the usual SNS transport theory of clean limits.

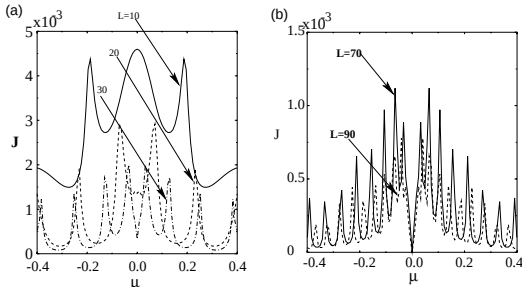

Fig. 3. The chemical potential dependence of the DC Josephson current through the zigzag ribbon of width $N = 10$ for (a) $L = 10, 20, 30$, and (b) $L = 70, 90$, where $1/\beta = 0.001$

The small oscillation is due to the multiple Andreev scattering at the interface between superconductor and nanographites. In Fig. 2(b), we show the chemical potential dependence of the current through the semiconducting armchair ribbons. The current rapidly decreases to the junction length for $|\mu| < E_g$, where E_g is the energy gap of the semi-conducting armchair ribbons. The length dependence of the currents is exponential decay.

In Fig. 3, we show the chemical potential dependence of the DC Josephson current through the zigzag ribbons, where $\beta = 0.001$. At a glance, we found the many resonant-tunneling-like peaks, which do not appear in the metallic armchair ribbons. Around $\mu = 0$ we found the large dip structure, because the group velocity in the zigzag ribbon rapidly decreases around the $\mu = 0$. We have also checked that the coupling strength between superconductor and graphite ribbons does not change the profile of the peak structure of the Josephson currents.

In conclusion, we have presented the preliminary results of DC Josephson currents through the nanographite ribbons based on the tight binding model with the thermal Green function techniques. It is found that the behavior of the DC Josephson current crucially depends on the edge structures of nano-graphite ribbons. Further analyses will be presented elsewhere.

References

[1] K. Wakabayashi *et. al.*, Phys. Rev. B**59** (1998) 8271.

[2] A. F. Morpurgo *et. al.*, Science **286** (1999) 1508.

[3] M. Fujita et. al., J. Phys. Soc. Jpn. **65** (1996) 1920.

[4] A. Furusaki, Physica B **203** (1994) 214.