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Principle for Detecting Resonant States in Thermoelectric Materials Using a Superconductor Tunneling Junction

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Recent theoretical studies indicate that the existence of resonant states near the Fermi level can lead to a significant improvement in the thermoelectric figure of merit. Experimental investigation of this concept requires determination of the existence of these resonant states. In this paper, we report a theoretical calculation on the *I–V* characteristic of a thermoelectric/insulator/superconductor-based tunneling junction. The results show that the resonant states can be detected by measuring the *I–V* characteristic of such a superconducting tunneling junction, which provides a theoretical basis for development of a measurement technique to detect the resonant states for thermoelectric materials.

Key words: Thermoelectric materials, heavy fermion, resonant states

Heavy fermion metals, such as $YbAl_3$ and $CeAl_3$, exhibit significantly higher thermoelectric figures of merit than normal metals, mainly due to a significantly large Seebeck coefficient near Kondo temperatures.[1–4] Theoretical work by Mahan et al.[5] indicates that an increase in the Seebeck coefficient can be attributed to the existence of resonant states near the Fermi level in those heavy fermions. Recently, experimental work by Heremen et al. showed that an improvement in *ZT* can be obtained in a Tl-doped PbTe system. They suggested that the increase might be attributed to the possible existence of resonant states induced by Tl doping near the Fermi level.[6] Clearly, the capability to detect resonant states in such systems would provide direct confirmation of this hypothesis, which has important implications for thermoelectric research. In this paper, we report a theoretical finding that facilitates development of a measurement technique for detection of resonant states through measuring the *I–V* curve of a thermoelectric/insulator/superconductor tunneling junction.

Thermoelectric materials are heavily doped semiconductors in which the Fermi level is usually very close to or enters the conduction-band edge. If there exist resonant states near the Fermi level, the density of states of such materials can be viewed as a superposition of the usual density of states and a narrow band of resonant states, as shown in Fig. 1, where b and a are the heights of the usual density of states and resonant states, respectively; δ is the width of the resonant states band. If such a material is brought into contact with a superconductor through a very thin insulating layer (usually, a few nanometers), a tunneling junction as shown in Fig. 2a can be formed. It is anticipated that the properties of the materials involved in such a junction may be deduced from the *I–V* curves of such a structure. In fact, tunneling junctions with a normal-metal/insulator/superconductor structure have previously been investigated for various applications, including electron tunneling refrigerators for milli-Kelvin cooling,[7] cold electron bolometers for astronomical detectors,[8] and electron tunneling spectroscopy for determining superconducting gaps[9] and investigating the Andreev reflections on heavy-fermion superconductors.[10] In this investigation, we employ a similar approach using a tunneling structure in which the normal metal is replaced by a heavily doped thermoelectric material with an assumption that resonant states exist near the Fermi level.

Figure 2b shows a schematic band diagram of a thermoelectric/insulator/superconductor junction.

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