Thermal Power Generation in Silicon Diodes

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Thermoelectric converters are used to generate electrical power from waste heat, for example, from the exhaust system of automobiles. The generated electricity can supplement the power needs of the system as well as reduce the cooling requirements. Since these devices do not have moving parts, they are extremely reliable. In this work electrical and thermal properties of several silicon diodes have been investigated. Preliminary results suggest that these diodes work as thermionic power generators.

1. Introduction

Thermoelectric materials can convert electrical energy directly to thermal energy and vice versa, thus can be used as either refrigerators or power generators [1,2]. Since these thermoelectric converters (TECs) do not have mechanical moving parts, they virtually last forever. Importantly, solid-state TECs offer a possibility of in-situ cooling of high-power electronic and optoelectronic devices by integration into these devices. Alternatively, TECs can used to generate electrical power from waste heat, for example, from the exhaust system of vehicles. The electricity generated may not only supplement the power need of a system but may also reduce the cooling requirements of its circuit components.

Thermoelectric power generators are based on Seebeck effect, i.e. two dissimilar junctions at different temperatures produces a voltage across the junctions. Figure 1 shows a schematic diagram of a simple thermoelectric power generator which comprises p-type and n-type elements connected electrically in series and thermally in parallel. Heat is pumped into one side of the junction and pumped out from the other side. Thermionic devices operate according to Richardson's equation - the current per unit area emitted by a hot surface at a temperature T with a work function ϕ is given by $J_R(\phi,T) = AT^2 e^{-e\phi/k_B T}$, where K_B is the Boltzmaan's constant and $A = \left(emk_B^2\right)\left(2\pi^2\hbar^3\right)^{-1} \approx 120A/cm^2K^2$. Hence electrons can escape from a hot surface if their kinetic energy exceeds the work function of the material, thus producing electric current.

The conventional TE power generator with metallic electrodes has several limitations including high manufacturing costs and operational temperatures above 1000 °C in order to have reasonable efficiencies. Thus their application is limited to where reliability is a prime factor or where other technologies are not viable, such as nuclear power converters in space probes and satellites. If the efficiency can be improved, TE generators can be used for many other applications. Mahan [3] predicts that thermionic device efficiencies as high as 80% of the Carnot value are possible.

The efficiency of thermoelectric devices depends primarily on the thermoelectric figure of merit zT which is expressed as $zT = S^2\sigma T/\kappa$, where S is the Seebeck

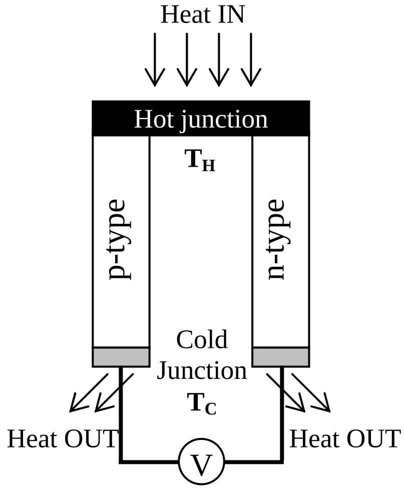

Fig. 1. Schematic diagram of a thermoelectric generator.

coefficient, σ is the electrical conductivity and κ is the thermal conductivity of the material [1]. At room temperature, the best known thermoelectric material Bi_2Te_3 has $zT \sim 1$. Thermoelectric coolers with $zT = 1$ operate at 10% of the Carnot efficiency. Recently several ideas have been put forward for the optimisation of zT, including quantum confinement in nanostructured materials [4-6].

In this work we have investigated electrical and thermal properties of silicon diodes. Preliminary results indicate that these diodes works as thermionic power generators.

2. Experimental details

Several silicon "bare" diodes were prepared by ion implantation**.** A schematic diagram of the diodes is shown in Fig. 2(a). A 350 μm silicon wafer was doped with boron (10^{14} ions/cm^2) and phosphorous (10^{15} ions/cm^2), respectively. Metal contacts (Al) were deposited on the top and the bottom surfaces as indicated in the diagram. IV-diagrams of two representative diodes, as given in Fig. 2(b), indicate the expected behavior.

The experimental setup employed in this work is illustrated in Fig. 3. A temperature gradient across the silicon diode is produced by heating the bottom of the diode with a commercially available Melcor TE cooler. (Although this device is primarily used as a cooler, in this case it is used as a heater.) The temperature at the bottom and at the top surface of the diode was measured using two multimeters connected with type K thermocouples, as indicated in Fig. 3. The temperature resolution of the probe was 1 °C. The voltage generated across the diode was measured with a third multimeter. In order to avoid the influence extraneous environmental factors, such as the photovoltaic effect, the experimental setup was housed in an alluminium cylinder.

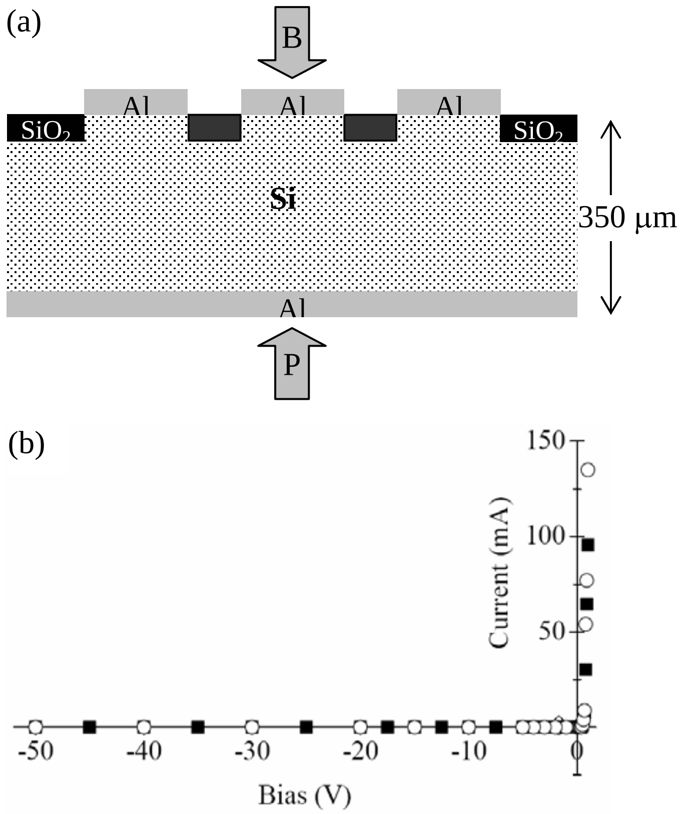

Fig. 2. (a) Schematic diagram of silicon diodes used in this work (not to scale). (b) IV characteristics of two representative diodes.

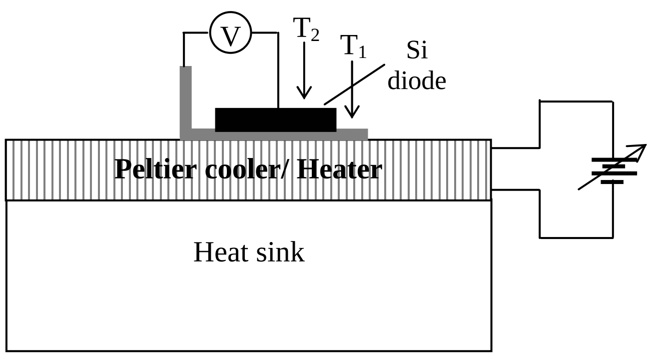

Fig. 3. Experimental setup employed in this work (not to scale).

3. Results and discussion

Fig. 4(a) shows the voltage generated across a diode as a function of time. The "ON" and the "OFF" in the diagram corresponds to the events when the bias to the heater was applied and when it was removed.

It is evident that a voltage across the diode is generated when a bias is applied to the heater. The voltage disappears when the bias is removed. This voltage can thus be associated with the temperature gradient produced across the silicon diode. It is also evident from the diagram that the output voltage increases as the bias is increased. This is expected as a high bias provides more heat to the bottom of the silicon diode thus producing a large temperature gradient across the diode.

Figure 4(b) shows the measured average voltage output across the diode as a function of temperature difference between the hot and cold sides of the diode. Here again an increase in the output voltage is observed with an increase in the temperature gradient across the diode. The solid line is a best fit which agrees well with the data. Thus over this small range, the observed output voltage is directly proportional to the temperature gradient across the diode.

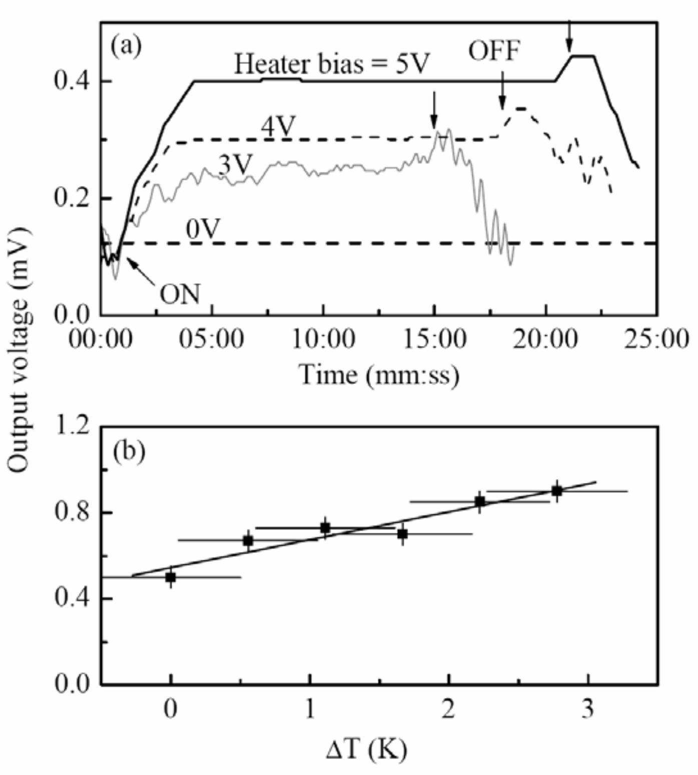

Fig. 4. (a) Voltage generated by a silicon diode. The output voltage increases with the heater bias. (b) The voltage generated by a silicon diode as a function of temperature gradient.

4. Conclusion

Thermal and electrical properties of several silicon "bare" diodes have been investigated. Thermal power generation of silicon diodes has been observed. On the basis of the temperature dependence, the mechanism is believed to be thermionic in nature, but a small thermoelectric effect may be present. The observed power generation for a single diode is small for these small temperature differentials. However, it will be greatly increased as the temperature differentials are greater, as would be expected in practice.

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