Electric field effect controlled thermoelectricity in thin Bi films

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Abstract

We demonstrate here, for the first time, the feasibility of enhancing the thermoelectric properties, by electric field effect controlled doping. The experimental data, on thin Bi films reported here, confirm the considerable enhancement of the Seebeck voltage. It should be noted that Bi may not be the most effective thermoelectric to use in this context. Some of the narrow-gap semiconductor thermoelectrics, presently investigated, carry an even larger potential of improved thermoelectric properties.

Key words: thermoelectrics; electric field effect; Bi films

In a recent paper [1,2] we presented the theory of an Electric-Field-Effect (EFE) induced increase of the thermoelectric figure of merit M of a thin film thermoelectric TE plate in a capacitive structure. This can be applied e. g, to the case of a LT Peltier cooler where, under EFE, the positively charged TE plate becomes the $p-$type arm while the negatively charged TE plate becomes $n-$type arm.

A route, alternative to the conventional chemical doping, to modify a wide spectrum of physical properties of nanoscale sized films, by dynamically varying the concentration of the carriers by an applied electric field (Electric field effect doping -$EFED$), has been proposed recently [1–6]. $EFED$ is applicable for thin films of narrow-gap semiconductors (e. g. $PbTe$, $SnTe$, $PbSe$, PbS etc.) and semimetals (such as Bi) that posses a large enough dielectric constant, so that their typical screening lengths are 100-1000 Å .

In the present paper we choose to demonstrate the effectiveness of $EFED$ in controlling the thermoelectric characteristics of thin Bi films. The basic physical principles and the feasibility model calculations have been described in two of our recently published articles [1,2].

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A measure of the thermoelectric quality is the dimensionless figure of merit $M = \sigma S^2 T/\kappa$, [7], where T is the temperature, σ is the electroconductivity, S is the Seebeck coefficient and κ is the thermal conductivity. Most present-day TE materials have values of $M \leq 1$. Applying $EFED$ can increase markedly the value of M.

The EFE-Doping. Applying a sufficiently high gate potential V_g of corresponding polarity, an intrinsic semiconductor with a thickness L smaller than its screening length L_S, under EFE-conditions, can be converted into an n- or p-type monopolar semiconductor. A typical dielectric constant of the dielectric layer is $\simeq 5 \div 10$. The maximum breakdown field for the best dielectrics is $E_d \simeq 10^7$V/cm, thus the maximum electric displacement is $D_d \simeq 10^8$ V/cm, giving a surface charge of 5.5×10^{13} [e]/cm^2. Thus, for a $L \simeq 550$ Å thick semiconductor film, the average concentration is $n = 10^{19}$ cm^{-3}. Using the formula determining L_S for a non-degenerate semiconductor, $L_S = \sqrt{\varepsilon kT/4\pi e^2 n}$, where k is the Boltzmann constant and $T = 300$ K, we obtain a dielectric constant of $\varepsilon \simeq 210$ for the semiconductor. The narrow gap semiconductors $A_{IV}B_{VI}$ and $A_V B_{VI}$ are known to possess such high dielectric constant (at $T = 300$ K $PbTe$ has $\varepsilon = 412$, Bi_2Te_3 has $\varepsilon \simeq 100$). To obtain a practical value for L, a large L_S is required, i.e. a large ε. This also guarantees that

the $EFED$ will be relatively homogeneous over the layer thickness. It should be emphasized that $EFED$ allows to vary both the *type* of the *majority carriers* as well as their *concentration* over a wide range.

Since, in general, the semiconductor under $EFED$ becomes inhomogeneous, the averaging over the sample volume depends on the specific phenomenon considered. Thus, just as in the case of the effective figure of merit, $\tilde{M}$ [1], any property f has to be averaged over the film thickness

$$\langle f \rangle = \frac{1}{L_z} \int_0^{L_z} f(z)\, dz, \qquad (1)$$

where L_z is the film thickness. To perform such averaging, one has to calculate first the profiles of electron and hole concentrations $n(z), p(z)$, under $EFED$ conditions. The dependence on z enters implicitly trough the z-dependence of the electrostatic potential $\varphi(z)$, which is a solution of the corresponding Poisson equation for the $EFED$ semiconductor structure. The procedure corresponding to the simple planar $EFED$ unit has been described in Ref. [1].

Experimental. We present here the results of experimental investigation of electric field effect controlled Seebeck voltage S^{EFE} in a thin (∼350 Å thick) Bi film thermally evaporated in vacuum (¡10^{-7} torr) on a heated thin (∼10 μm) mica substrate. On the opposite side of the substrate a 2000 Å thick gold layer (the gate) was deposited, completing the capacitor structure. A voltage of up to ±1000 V between the Bi-film and the gate provided the required electric field interval from $+10^8$ V/m to -10^8 V/m. The field dependence of $S^{EFE}(E)/S^{EFE}(E=0)$ at two temperatures, $T = 90$ K and $T = 240$ K is shown in Fig. 1. The quasi-linear dependence of $S^{EFE}(E)$ near $E = 0$ for a compensated sample($n \cong p$) is also corroborated by theoretical calculation, see Ref. [2]. Fig. 2 shows the temperature dependence of $B_S \equiv dS^{FEE}/dE$. As

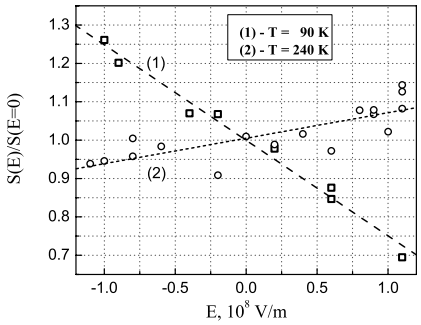

Fig. 1. The electric field dependence of the normalized Seebeck coefficient in a 360 Å thick Bi film at (1) 90 K and (2) 240 K.

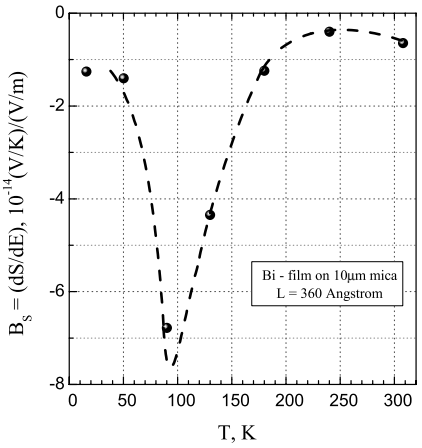

Fig. 2. The temperature dependence of the derivative of the Seebeck coefficient w.r.t. the electric field, near E=0.

$S^{EFE}(E=0)$ changes sign from "+" (below 210 K) to "−" (above 210 K), B_S remains negative in the *whole* temperature region. The negative sign of B_S is a clear indication that $n \cong p$. Breaking the compensation would bring about a change in the sign of B_S. The maximum of the effect at ∼90 K, demonstrates the possibility of optimizing the thermoelectric properties of the Bi film by $EFED$.

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