of the Grüneisen parameter calculated from the single crystal and the polycrystal TOEC with that calculated from bulk data. Using values for the linear expansion coefficient, $\alpha=7.02\times10^{-6}$ °C^{-1}, and specific heat, $C_v=0.065$ cal g^{-1} °C^{-1} obtained from handbooks and the density $\rho=8.578$ g/cm^3, and isothermal bulk modulus, $K^T=1.687\times10^{12}$ dyn/cm^2 obtained in the present study in the relation

$$\gamma_B=3\alpha K^T/C_v\rho \tag{4}$$

gives the value for the bulk Grüneisen parameter of $\gamma_B=1.52$. Using the methods of Ref. 4 for obtaining the Grüneisen parameter from the elastic constants by averaging the contribution of 39 pure-mode phonons to that parameter results in values of $\gamma_{SC}=1.511\pm0.026$ and $\gamma_{PC}=1.546\pm0.092$ for the single crystal and the polycrystal, respectively. A useful calculational equation for the polycrystal Grüneisen parameter which can be obtained from the equations of Brugger[4] by imposing isotropy conditions is

$$\gamma_{PC}=(K^Tm_1'-\Delta K)/6C_{11}{}^S+(K^Tm_2'-\Delta K)/3C_{44}{}^S, \tag{5}$$

where m_1' and m_2' are the measured hydrostatic pressure slopes for the polycrystal and $\Delta K=K^S-K^T$ is the difference between the adiabatic and isothermal bulk moduli.

A second check on the values of the TOEC determined here is to compare the measured polycrystal constants with values calculated from the single-crystal constants. Recently, equations permitting this comparison were derived[30] using strain-energy density considerations with the approximation that a uniform state of strain acting on the surface of a homogeneous, quasi-isotropic, polycrystalline body produces a uniform strain throughout the body. This development, analogous to that of Voigt relating the second-order elastic constants,[31] leads to the following relations between the TOEC:

$$\begin{aligned}
\nu_1&=\tfrac{1}{35}(C_{111}+18C_{112}+16C_{123}-30C_{144}-12C_{166}+16C_{456})\\
\nu_2&=\tfrac{1}{35}(C_{111}+4C_{112}-5C_{123}+19C_{144}+2C_{166}-12C_{456})\\
\nu_3&=\tfrac{1}{35}(C_{111}-3C_{112}+2C_{123}-9C_{144}+9C_{166}+9C_{456}).
\end{aligned} \tag{6}$$

Using the values of C_{ijk} for columbium given in Table III in these equations results in $\nu_1=-4.59\pm0.38$, $\nu_2=-3.80\pm0.15$, and $\nu_3=+0.78\pm0.09$, all in units of 10^{12} dyn/cm^2. These values are seen to be in very good agreement with the values measured for the polycrystal sample B shown in Table V which provides an indirect check on both sets of TOEC.

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[30] R. Chang, Appl. Phys. Letters **11**, 305 (1967).
[31] W. Voigt, *Lehrbuch der Kristallphysik* (B. G. Tuebner, Leipzig, 1928), p. 962.