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LETTER TO THE EDITOR

Phonon subbands observed in electrically heated metal wires

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Abstract. The steady-state electron heating characteristic of narrow metallic wires deposited on silicon substrates is shown to exhibit a periodic resonance structure. Using the quantum corrections to the resistance of the wire to estimate the electron temperature, we are able to determine the energy of each resonance. We show that these energies agree with the subband energies of the spatially confined phonons in the wire. From the energy separation of the resonances we have made the first direct measurement of the velocity of sound in nanometre scale wires.

Recent investigations of the non-equilibrium properties of metallic thin films have shown the importance of considering the phonons within the microstructure itself [1, 2]. One technique employed to study the non-equilibrium properties of microstructures has used an applied electric field E to heat the electrons above the ambient temperature of the lattice. With this technique it has been shown that the steady-state phonon distribution in thin metal films is far from equilibrium [3]. Furthermore, it has been suggested that below a certain frequency the phonons in the film have a two-dimensional density of states, arising from spatial confinement by the film thickness. In this letter we describe an electron heating experiment performed on nanometre scale metallic wires. The electron heating characteristics show periodic structure that can be assigned to spatially confined phonon modes of the wire.

Twenty-five parallel $Au_{60}Pd_{40}$ alloy wires that were thermally evaporated onto a silicon substrate at room temperature and at a pressure of 5×10^{-6} Torr were used as samples for the experiments. No attempt was made to remove the native oxide layer from the silicon before thermal evaporation of the wires. The wires were delineated by electron beam lithography, and were 18 nm thick and 50 nm wide. The sheet resistance of the wires at 4.2 K was $R_{\square} = 12\ \Omega$. The samples were designed for true four-terminal measurement with an active sample length of 10 μm, as shown in figure 1. They were mounted inside a sealed copper chamber that was thermally attached to a temperature controlled helium bath. This arrangement ensured a good thermal contact to the silicon substrate and enabled the substrate temperature to be controlled to be better than 1 mK over the temperature range 1 to 4.2 K. The chamber could be either evacuated or filled with helium so that the exposed surfaces of the Au–Pd wires were either in vacuum or covered with liquid helium. This arrangement allowed the electron-heating effects to be studied as a function of the acoustic boundary conditions on the wires.

Resistance measurements were made using a low-frequency four-terminal bridge [4], and signal averaging. With this technique a fractional resistance change of one

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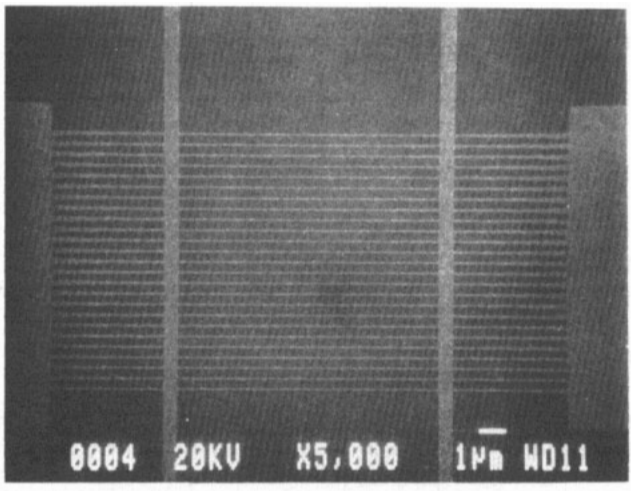

Figure 1. An electron micrograph of the Au–Pd wire samples. The two vertical stripes are the voltage contacts.

part in 10^6 could be detected with sensing currents as low as 120 nA per wire. Electron heating was provided by a DC electric field of up to 30 V cm^{-1} applied across the wires. The AC sensing bias was always kept sufficiently low that its contribution to the heating remained negligible.

The equilibrium resistance change, $(R - R_0)/R_0 = \Delta R/R_0$, of the wires as a function of the substrate temperature is shown in figure 2. A minimum resistance R_0 is observed at $T_0 = 8$ K below which the resistance increases as approximately $T^{-1/2}$. To within experimental error no difference was found in the equilibrium resistance change with the chamber evacuated or filled with liquid helium. The resistance correction we observe is similar to those reported by other workers for one-dimensional Au–Pd wires [5, 6], and is consistent with the experiments reported by Lin and Giordano [7] who have shown that the dominant resistance correction term in Au–Pd films and wires is due to electron–electron interactions [8].

In figure 3, the steady-rate resistance change of the wires with applied electric field, $(R(E) - R_0)/R_0 = \Delta R(E)/R_0$, at three substrate temperatures in vacuum is shown. There are two important features of the data; first, the steady-state resistance falls below R_0 at applied fields greater than 5 V cm^{-1}, and second, periodic resonances are observed with increasing electric field. The resonant features were not observed in Au–Pd films of similar sheet resistance and thickness that were fabricated concurrently adjacent to the wire samples. The position of the resonances was independent of the substrate temperature and the sweep direction of the applied field, but the magnitude of the resonances did change with substrate temperature, as seen in figure 3. Curve D in the inset to figure 3 shows the steady-state resistance data at 1.5 K after they were passed through a high-pass digital filter to remove some of the background. A Fourier transform of the data indicated a single dominant component corresponding to a periodicity in the electric field of 2.9 V cm^{-1}, as shown in the inset to figure 4. Curve E in the inset to figure 3, and figure 4 show that when helium was condensed in the chamber the position of the peaks shifted systematically. This result clearly shows that the acoustic boundary conditions at the surface of the wires affect the electron-heating characteristics. It also highlights an important experimen-

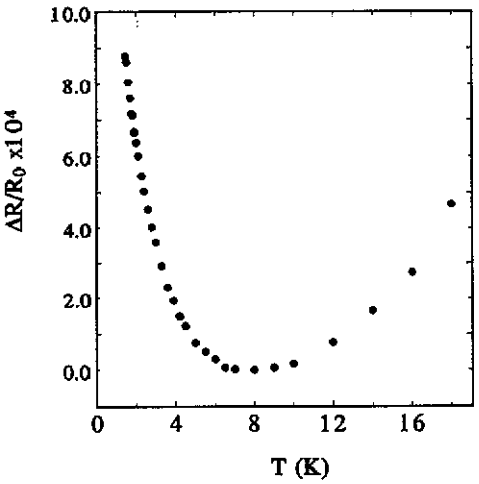

Figure 2. The equilibrium temperature dependence of $\Delta R/R_0$.

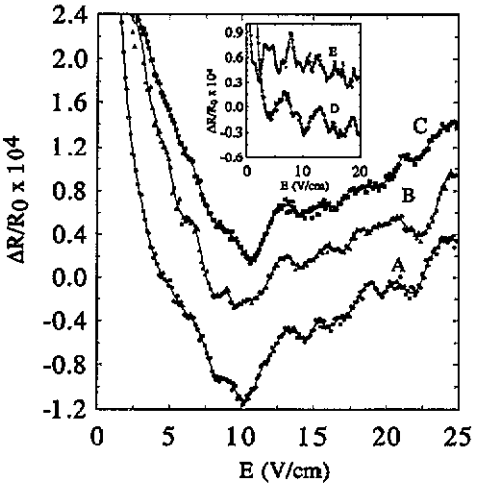

Figure 3. The electric field dependence of the resistance at the substrate temperatures 1.5 K (A), 3.0 K (B), and 4.0 K (C). Curve D in the inset shows the 1.5 K data in vacuum and curve E shows the 1.8 K data in helium after they were passed through a high-pass digital filter to reduce the background. For clarity the traces in the figure and inset are offset by $\Delta R/R_0 = 5 \times 10^{-5}$.

tal point. At the beginning of each experiment the chamber was flushed with helium and then pumped for at least three days at room temperature. If the chamber was pumped for only a few hours, the position of the peaks was found to be between the data from the sample pumped for several days and the data from the sample in liquid helium, as shown in figure 4. We will address this point below.

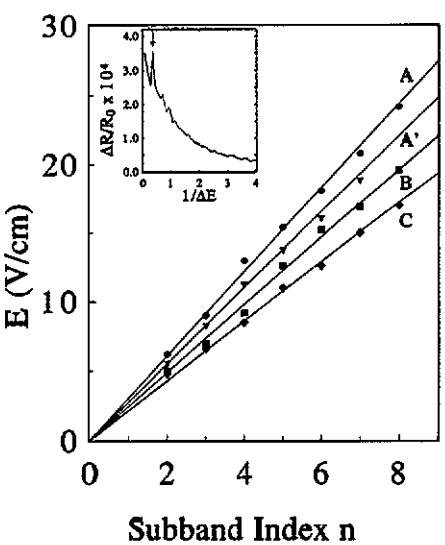

Figure 4. The position of the resonances plotted versus subband index. The positions of the resonances are the average values taken from traces at 1.5, 1.8, 2.4, 3.0, 4.0 K. The inset is the Fourier transform of $\Delta R(E)/R_0$ for the wires in vacuum, and the arrow indicates the dominant component.

The observation that in the presence of the electric field the steady-state resistance may be reduced below R_0 is similar to an effect observed previously in thin film samples [2, 9], but we believe this to be the first report of the effect in wires. The origin of this phenomenon may be understood by considering the sum of the low-temperature resistance corrections and a Drude component of resistance that give the equilibrium resistance as a function of temperature. Each component has a different dependence on the electron and phonon distributions within the wires. Therefore, when the electrons and phonons are moved out of equilibrium by the applied electric field, the relative magnitudes of the components change which can cause the minimum steady-state resistance to be below R_0 [3]. Since the dominant resistance correction term in Au–Pd wires is due to interactions [7], which depend only on the electron temperature, to a good approximation we can use the resistance correction to estimate the electron temperature T_e in the wires.

Features in the steady-state conductance of metallic wires as a function of the bias current have been reported previously and were shown to be due to universal conductance fluctuations (UCF) [10]. For several reasons we do not consider UCF to be the origin of the features we observe in $\Delta R(E)/R_0$. First, the Fourier transform shows one dominant period, which is not typical of UCF [10]. Second, the length of the wires, and the fact we have 25 in parallel, with considerable electron heating by the DC current, are expected to depress UCF in our samples. In $\Delta R(E)/R_0$ we did observe some signals of magnitude 5 in 10^6 that were not reproducible; these are most probably UCF. Third, the systematic manner in which the periodicity of the peaks changed when the acoustic boundary conditions were altered suggests a mechanism other than UCF.

To interpret the features in the electron-heating data from the wires in a vacuum, we discuss the phonon spectrum in the wires. The phonon dispersion for uncoupled modes in a wire has the form [11],

$$\omega^2 = V_s^2[q^2 + (n\pi/W)^2 + (m\pi/d)^2] \tag{1}$$

where d and W are the thickness and width of the wire, respectively, V_s is the velocity of sound, and q is the wavevector along the wire. The integers n and m are the subband indices. In general, for a given pair of subband indices n and m, three subbands exist: one for the longitudinal and two for the transverse modes. When n and m are both zero, the phonons will be effectively one dimensional. The temperature at which one-dimensional behaviour is expected can be estimated by equating the dominant phonon wavelength $\lambda_{ph} \approx V_s h/2k_B T$, to the largest dimension, either d or W. At 1 K, using the bulk value of the longitudinal velocity of sound, $V_l = 4.1 \times 10^3$ m s^{-1} obtained from a weighted average of Au and Pd values [12], both W and d are less than $\lambda_{ph} \approx 98$ nm. Therefore, at the lowest temperatures of the present experiments, the longitudinal phonon spectrum is anticipated to be modified. We note, however, that this argument only provides a rough estimate of the temperature range over which the phonon spectrum is modified because the phonon subbands are expected to be well defined up to energies at which the phonon mean free path due to anharmonic processes becomes comparable with W and d [3].

The resonances observed in $\Delta R(E)/R_0$ appear to be associated with the width of the wire since they were not found in the data from 1 μm wide films of similar thickness. From (1) the subband energies due to the wire width are $\epsilon = V_s n\pi\hbar/W$. Using the equilibrium resistance correction in conjunction with the initial slope of the

non-equilibrium data we estimate that $dT_e/dE = 0.65\ K\ V^{-1}$ cm, which is consistent with the linear dependence between E and T_e predicted for a one-dimensional system [13]. From this relationship we have determined the energy of each resonance, and a least-squares-fit to the energy versus subband index gives a slope of 1.9 ± 0.1 K from which we obtain a sound velocity of $V_s = 3.9 \pm 0.2 \times 10^3\ m\ s^{-1}$. This velocity is in good agreement with V_t and appears to be the first measurement of the velocity of sound in Au–Pd alloy. More importantly, it is the first experimental determination of the velocity of sound in a nanometre scale wire and shows the value is close to that of the bulk.

To support our explanation that spatially confined phonon modes cause the resonances, we note that a zero-wavevector phonon corresponding to no relative particle displacement is a solution to the equation of motion for elastic waves in an acoustic waveguide. This agrees with the present data since the fits shown in figure 4 can be extrapolated through the origin. Also, we have estimated the half-width of the peaks and find $\Delta\epsilon/\epsilon = 0.18$. This value can be equated with $\Delta W/W$ to predict a variation of ± 9 nm in the width of the wire. This is in close agreement with the value of ± 8 nm obtained from high-magnification electron micrographs of the wires.

Now we consider the shift in the peak positions when the acoustic boundary conditions on the wire are changed by immersion in liquid helium. Assuming the velocity of sound in the wire does not change with the boundary conditions, the data suggest the phonon subband energies are more closely spaced. This is seen in curves B and C of figure 4, for normal and superfluid helium, respectively. Curve A′ of figure 4 shows data after pumping the chamber for only a few hours, as described above. Since these data lie between the vacuum and normal helium data (curves A and B in figure 4, respectively), we believe residual helium remained adsorbed on the wires causing the subband spacing to be less than was found under more stringent vacuum conditions. The change in the subband spacing as the boundary conditions are modified is consistent with a reduction in subband spacing expected when the phonon confinement is changed from hard wall to a situation in which the phonons in the wire can couple to a surrounding medium.

Finally, we discuss the fact that we do not resolve the subbands associated with the transverse velocity of sound or the thickness of the sample. Taking a weighted average of the bulk transverse velocities for Au and Pd [12], we expect a subband spacing almost one half the spacing of the subbands associated with the longitudinal velocity of sound. Thus, half the transverse subbands will coincide with the resonances observed and the others will be midway between the observed peaks. Broadening by both the temperature and the width variation of the wires may cause them to be unresolved in the present experiments. However, we cannot rule out the possibility that the electron coupling to phonons in the transverse subband is weaker than it is to phonons in the longitudinal subband. It is most likely that we do not see the subbands associated with the sample thickness because they are broadened by the coupling to the substrate.

In summary, we have evidence for the existence of phonon subbands in narrow metallic wires. From the subband spacing we have made the first measurement of the longitudinal velocity of sound in small Au–Pd wires and have found it to be close to the expected bulk value.

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References

[1] Bergmann G, Wei Wei, Zou Yao and Mueller R M 1990 *Phys. Rev.* B **41** 7386
[2] Nabity J C and Wybourne M N 1990 *Phys. Rev.* B **42** 9714
[3] Nabity J C and Wybourne M N 1991 *Phys. Rev.* B **44** 8990
[4] Moody M V, Paterson J L and Ciali R L 1979 *Rev. Sci. Instrum.* **50** 903
[5] Giordano N 1980 *Phys. Rev.* B **22** 5635
[6] White A E, Tinkham M, Skocpol W J and Flanders D C 1982 *Phys. Rev. Lett.* **48** 1752
[7] Lin J J and Giordano N 1987 *Phys. Rev.* B **35** 545
[8] Al'tshuler B L, Khmel'nitzkii D, Larkin A I and Lee P A 1980 *Phys. Rev.* B **22** 5142
[9] Liu J, Meisenheimer T L and Giordano N 1989 *Phys. Rev.* B **40** 7527
[10] Webb R A, Washburn S and Umbach C P 1988 *Phys. Rev.* B **37** 8455
[11] Auld B A 1973 *Acoustic Fields and Waves* vol 2 (New York: Wiley) ch 10
[12] McGinnis W C and Chaikin P M 1985 *Phys. Rev.* B **32** 6319
[13] Sarker S K, Hu Y K, Stanton C J and Wilkins J W 1987 *Phys. Rev.* B **35** 9229