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Resistivity and magnetoresistance studies on superconducting $A15$ V_3Ga, V_3Au, and V_3Pt compounds

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Resistivity and magnetoresistance measurement have been made on $A15$ V_3X ($X =$Ga, Au, and Pt) compounds. The low-temperature resistivity $\rho(T)$ ($T_c < T < 40$ K) of V_3Ga and V_3Au shows a T^2 dependence whereas that of V_3Pt exhibits a T^3 dependence. The magnetoresistance of V_3Ga and V_3Pt varies as $H^{1.6}$ and that of V_3Au shows a linear field dependence. These results are analyzed in terms of existing theories.

I. INTRODUCTION

Previous studies have shown[1–6] that the resistivity $\rho(T)$ of $A15$ compounds differs significantly from that of a metal at both low and high temperatures. However, a large number of such studies has been made to understand the temperature dependence of $\rho(T)$ of only few high-T_c $A15$ compounds. Few efforts[7–9] have been made to understand the $\rho(T)$ of low-T_c compounds. The resistivity behavior of low-T_c $A15$ compounds at high temperatures is similar to that of a high-T_c $A15$ compound. The high-temperature $\rho(T)$ data are analyzed in terms of the parallel resistor model developed by Fisk and Webb.[6] However, at low temperatures, $\rho(T)$ of the low-T_c compounds shows a higher power-law dependence of T compared to that of high-T_c $A15$ compounds. For example, $\rho(T)$ of Mo_3Ge ($T_c = 1.5$ K) (Ref. 7) varies as T^5 and that of Nb_3Sb ($T_c = 0.2$ K) (Ref. 8) shows a $T^{3.6}$ dependence at low temperatures. We have observed that $\rho(T)$ of Ti_3Sb (Ref. 9) shows a T^2 behavior at low temperatures.

Several attempts exist in the literature to account for this anomalous behavior of $\rho(T)$ at low temperatures. However, none of them gives a successful explanation. For instance, Webb *et al.*[8] have suggested that the phonon spectrum of these compounds may be different from the simple Debye behavior $[F(\omega) \sim \omega^2]$ in such a way as to produce a T^2 dependence. Later, Gurvitch *et al.*[10] have shown that such an approach is not valid because even in highly disordered Nb_3Sn (whose phonon spectrum is different from the unirradiated one), one finds a T^2 dependence for $\rho(T)$. Cote and Meisel[11] have tried to explain the observed T^2 dependence in $A15$ compounds using Pippard's concept of phonon ineffectiveness which was originally used to explain the ultrasonic attenuation by the electrons. Allen[12] has questioned the validity of this model on both theoretical and experimental grounds. Recently, Lee and Ramakrishnan[13] have shown that the model developed by Cote and Meisel is inconsistent with the microscopic theory. Furthermore, Caton and Viswanathan have observed a linear dependence in $\rho(T)$ (with a negative slope) with temperature for heavily damaged (neutron) V_3Si samples. This result contradicts the T^2 dependence predicted by Cote and Meisel.[11]

Hasegawa[14] has speculated that the T^2 term in disordered transition-metal alloys can result from the nonconservation of momentum in the electron-phonon scattering. One does not know whether such a theory is applicable to $A15$ compounds whose ρ_0 and A are much smaller than that of disordered alloys. Recently, Kaveh and Wiser[15] have suggested that the large values of A in the case of high-T_c $A15$ compounds can be explained by the enhancement of A due to strong phonon-mediation effects. In this paper we present the resistivity and magnetoresistance studies on V_3X ($X =$Ga, Au, and Pt) compounds.

II. EXPERIMENTAL DETAILS

All the V_3X ($X =$Ga, Au, and Pt) compounds are formed by melting the individual constituents (purity $> 99.9\%$) in an arc furnace in a high-purity argon atmosphere. The samples were melted at least five or six times to ensure homogeneity. The composition after each melting was corrected by assuming that all the weight loss was due to evaporation of Ga and Au in preparing V_3Ga and V_3Au alloys. The correction was small, amounting to about 5 wt. % of Ga and 2 wt. % of Au. The weight loss which occurred in melting the V_3Pt alloy was very small (less than 1%). The lattice constants were determined by an x-ray diffraction technique, which also showed that the samples have $A15$ structure. The resistance was measured by a four-probe dc method using ultrasonically soldered indium contacts. The temperature was measured using a silicon diode thermometer which was calibrated from 1.5 to 300 K.

III. RESULTS AND DISCUSSION

The structural and superconducting properties of V_3X ($X =$Ga, Au, and Pt) are given in Table I. Flukiger *et al.*[16] have studied the resistivity of V_3Ga from just above its T_c to room temperature. Their studies showed that the resistivity $\rho(T)$ of V_3Ga increases from about 20 $\mu\Omega$ cm at 16 K to 90 $\mu\Omega$ cm at 300 K. However, there have been no detailed studies on the temperature dependence of resistivity of V_3Ga. So far, to our knowledge,

TABLE I. Normal- and superconducting-state properties of V_3X (X = Ga, Au, and Pt).

Sample	T_c (K)	ΔT_c (K)	Lattice constant (Å)	χ(300 K) (10^{-6} emu/g)	χ(0 K)[a] (10^{-6} emu/g)	ρ(300 K) ($\mu\Omega$ cm)
V_3Ga	14.5	0.06	4.8196	5.40	8.22	86.59
V_3Pt	3.0	0.05	4.8155	2.32	2.54	115.40
V_3Au	2.0	0.15	4.8740	2.96	3.90	111.20

[a] Extrapolated value.

there have been no studies on the resistivity behavior of *A*15 V_3Au and V_3Pt compounds. The variation of $\rho(T)$ with T for the three samples are shown in Figs. 1, 2, and 3. The low-temperature resistivity behavior for the three compounds is shown in Fig. 4.

The low-temperature resistivity can be written as,

$$\rho(T)=\rho_0+AT^n , \tag{1}$$

where ρ_0 is the residual resistivity, and A and n are constants. The quality of the fit is determined by a parameter called percentage deviation ($\mathscr{D}$) and it is given by

$$\mathscr{D}=\sum_{i=1}^{N}(\chi_i^2/N)^{1/2}100 , \tag{2}$$

where

$$\chi_i=[\rho(\text{obs})-\rho(\text{fit})]/\rho(\text{obs}) . \tag{3}$$

The fitting analyses for the low-temperature resistivity data ($T_c<T<40$ K) of V_3X compounds are given in Table II. Here one finds that $\rho(T)$ of V_3Ga varies as T^2 which is similar to the behavior observed in V_3Si. The $\rho(T)$ of V_3Pt exhibits a T^3 dependence at these temperatures. The values of the coefficient A for several *A*15 compounds and the temperature region in which their $\rho(T)$ shows a T^n behavior are also given in Table II.

According to MacDonald,[17] a metal that undergoes a superconducting transition experiences a large low-temperature enhancement in the electron-phonon scattering. Kaveh and Wiser[15] have used this idea to propose a strong electron-electron scattering in high-T_c *A*15 compounds. Furthermore, they have stated that this interaction should be large at low temperatures but much smaller at high temperatures. This phonon-mediated enhancement of electron-electron scattering is expected to weaken at about $T=\Theta_D/10$. Since the Debye temperature Θ_D for all the high-T_c compounds is around 300—400 K, we would expect that the contribution to A from electron-electron interaction would begin to diminish at about 30—40 K. From Table III, we can see that $\rho(T)$ varies as T^2 only up to 30—40 K in these *A*15 compounds.

Additional evidence for this model comes from the mechanism proposed by Anderson *et al.*[18] and Gutfreund *et al.*[19] which states that the decrease in T_c of high-T_c *A*15 compounds is due to the fact that disorder enhances the effective Coulomb repulsion. When added to the attractive phonon-exchange interaction, this leads to the overall decrease in the magnitude of the effective electron-electron interaction, and hence lowering of T_c. Now if the phonon-mediated effective electron-electron interaction is weakened, we would also expect to observe a marked decrease in the low-temperature value of $A_{ee}(T)$. Gurvitch *et al.*[20] have measured the change of A upon irradiation of the samples of high-T_c *A*15 compounds with α particles. They have observed such a decrease in the AT^2 term, which is closely correlated with the decrease in T_c. This is of course precisely what would be expected

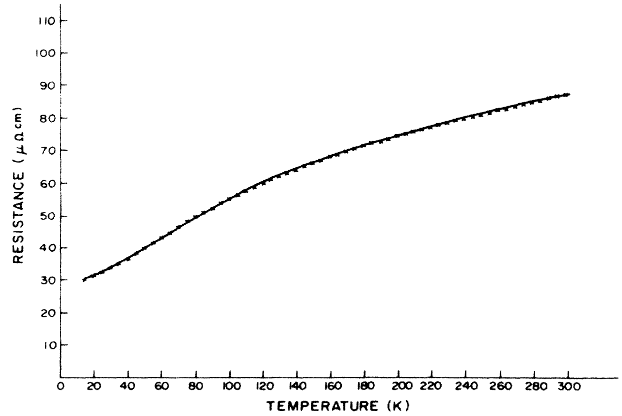

FIG. 1. Temperature dependence of resistivity of V_3Ga.

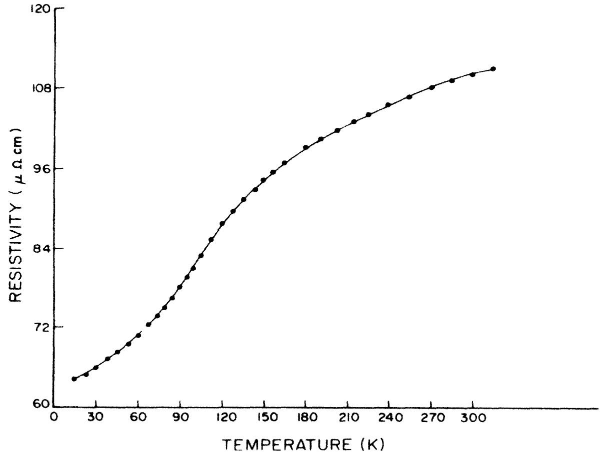

FIG. 2. Temperature dependence of resistivity of V_3Au.

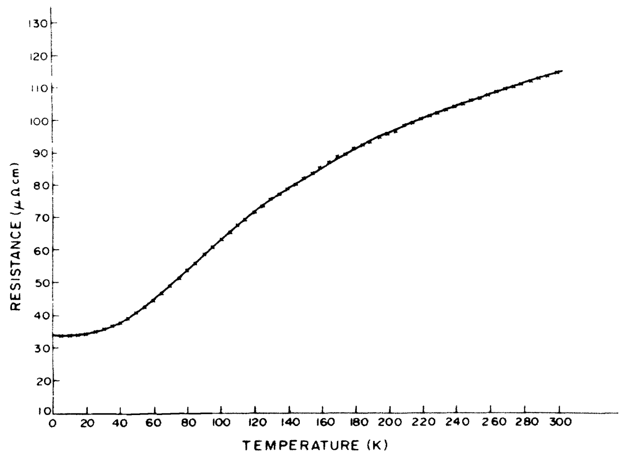

FIG. 3. Temperature dependence of resistivity of V_3Pt.

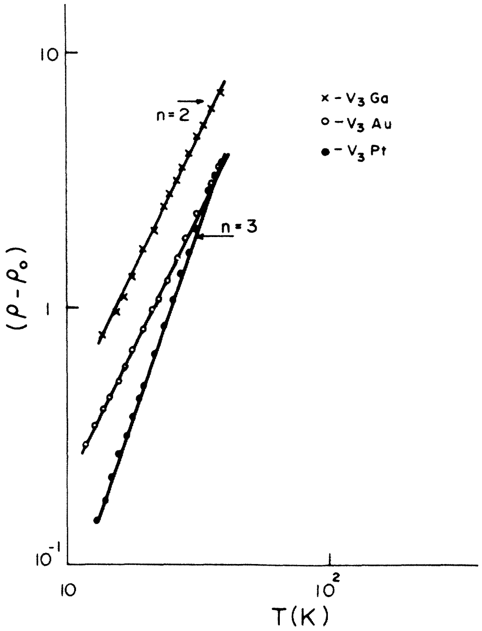

FIG. 4. Low-temperature resistivity of V_3X (X = Ga, Pt, and Au) compounds.

from the MacDonald theory and supports the identification of A with A_{ee}. Further evidence comes from the fact that the low-temperature $\rho(T)$ of both Mo_3Ge and Nb_3Sb does not have a T^2 dependence. Here the phonon-mediated electron-electron scattering is weak due to the low T_c of these compounds; hence, the normal electron-phonon scattering predominates over the electron-electron scattering.

Their explanation is strengthened when one considers the effect of irradiating a sample of Mo_3Ge. Unlike other $A15$ compounds, T_c of Mo_3Ge increases by a factor of 3 upon irradiation.[7] According to their ideas, this should increase the value of A_{ee}. Although the enhanced $A_{ee}T^2$ is still smaller than the electron-phonon scattering term above 10 K its presence should begin to be felt. This is confirmed by Gurvitch *et al.*[10] who observed that the value of n continues to decrease to 2 upon irradiation. Recently, Caton and Viswanathan have observed a strong correlation between γ^2 and the coefficient A (b in their paper). They have shown the values of both γ and b decrease with the decrease of T_c upon irradiation. This result is in agreement with the model proposed by Kaveh and Wiser.

However, we find that a low-T_c system like V_3Au (2.0 K) also shows a T^2 dependence of $\rho(T)$ at these temperatures while the $\rho(T)$ of V_3Pt exhibits a T^3 dependence. This result does not agree with the model proposed by Kaveh and Wiser as shown in Fig. 4 and the values of A are given in Table II.

The high-temperature $\rho(T)$ is fitted to the expression

$$1/\rho(T)=1/\rho_{0i}(T)+1/\rho_{\max}\ , \tag{4}$$

where the ideal resistivity ρ_{0i}, which can be characterized

TABLE II. Low-temperature resistivity data for $A15$ compounds.

Sample	T_c (K)	ρ_0 ($\mu\Omega$ cm)	A ($\mu\Omega$ cm/K^2)	n	T_1 (K)	T_2 (K)	$\mathcal{D}$ (%)
V_3Ga[a]	14.5	29.69	0.45×10^{-2}	2.0	16	40	0.10
V_3Pt[a]	3.0	33.88	0.47×10^{-4}	3.0	10	40	0.08
V_3Au[a]	2.0	63.73	0.27×10^{-2}	2.0	10	40	0.07
Ti_3Sb[b]	6.5	13.62	0.28×10^{-2}	2.0	9	36	0.13
Nb_3Au[b]	11.0	17.00	0.27×10^{-2}	2.0	12	40	0.13
Nb_3Sn[c]	~18		0.70×10^{-2}	2.0	19	~30	
Nb_3Al[c]	~19		0.20×10^{-2}	2.0	20	~40	
Nb_3Ge[c]	~22		0.60×10^{-2}	2.0	23	~35	
V_3Si[c]	~17		0.17×10^{-2}	2.0	18	~30	
Mo_3Ge[c]	~1.5			5.0			
Nb_3Sb[c]	0.2			3.6			

[a] This work.
[b] Data taken from Ref. 23.
[c] Data taken from Ref. 15.

TABLE III. Analysis for parallel resistor model for V_3X (X = Ga, Au, and Pt) compounds.

Sample	$\rho_{\max}$ ($\mu\Omega$ cm)	ρ_0 ($\mu\Omega$ cm)	Θ_m (K)	b	$\mathscr{D}$ (%)
As-cast V_3Ga	224.70	61.65	303.77	314.89	0.10
Annealed V_3Ga	204.60	38.50	300.05	393.24	0.12
As-cast V_3Pt	205.56	63.13	420.57	686.36	0.09
Annealed V_3Pt	181.93	41.85	390.00	723.42	0.11
Annealed V_3Au	180.00	70.50	430.50	650.20	0.15

in many ways, is in parallel with the saturation resistivity $\rho_{\max}$. One can write ρ_{0i} as

$$\rho_{0i}=\rho_0+\rho_i(T)\ , \tag{5}$$

where ρ_0 is the ideal temperature-independent residual resistivity without an additional saturation channel and $\rho_i(T)$ is the corresponding ideal temperature-dependent part. One can write $\rho_i(T)$ as

$$\rho_i(T)=b\,(T/\Theta_m)^r\int_0^{\Theta_m/T}\frac{x^r dx}{(e^x-1)(1-e^{-x})}\ , \tag{6}$$

where Θ_m is a cutoff temperature (similar to Θ_D) and b is the associated constant. This amounts to generalization of Wilson's theory ($r=3$) or the Bloch-Grüneisen model ($r=5$) for the ideal part of the resistivity.

The above-mentioned parallel resistor model fits fairly well to the $\rho(T)$ data between 50 and 300 K. Here, we find that Wilson's expression for $\rho_i(T)$ gives a better fit for $\rho(T)$. The results of the analysis are shown in Table III. The value of the cutoff temperatures are reasonable because they are very close to the Debye temperatures reported for these compounds.[21]

IV. LONGITUDINAL MAGNETORESISTANCE

In general, magnetic field will have little effect on electron-electron scattering. This is true in the case of a simple metal with a nearly spherical Fermi surface. Normal electron-electron scattering (NEES) does not contribute to the electron-electron scattering resistivity $\rho_{ee}(T)$ because NEES events conserve the total momentum and hence do not degrade the current. In this case, $\rho_{ee}(T)$ is solely determined by umklapp electron-electron scattering. However, this is true only in the case of an isotropic system. Any source of anisotropy in the system will cause NEES to contribute to $\rho_{ee}(T)$. The effect of strong magnetic field is to reduce the anisotropy and hence diminish the contribution of NEES to the resistivity. Although NEES events do not degrade the current, they do redistribute the electrons by scattering them into different states on the Fermi surface and by altering their trajectories. If the scattering probability is state-independent and the sample is infinite in extent, this redistribution will not affect the resistivity. However, if a source of anisotropic scattering is present or the sample is finite (thin wire) then $\rho_{ee}(T)$ will be affected by NEES driving some electrons into the surface of the sample or into a region of strong scattering on the Fermi surface.

According to Kaveh and Wiser,[15] one can diminish such anisotropy by the application of magnetic field and hence decrease the contribution of NEES to $\rho_{ee}(T)$. Furthermore, they have claimed that the data obtained by Michel *et al.*[22] on the magnetic field dependence of resistivity of aluminium have given indirect experimental evi-

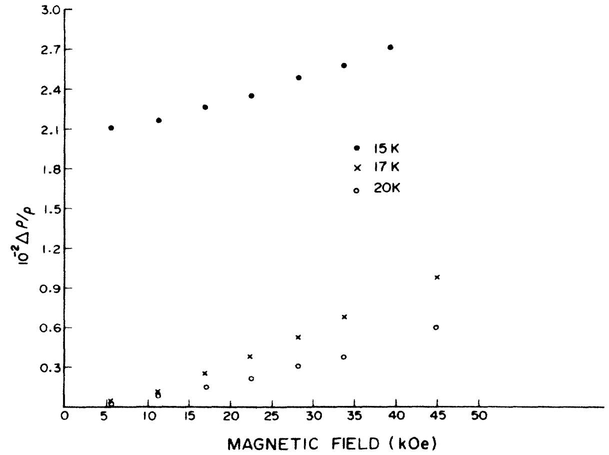

FIG. 5. Variation of longitudinal magnetoresistance $\Delta\rho/\rho$ of V_3Ga with field.

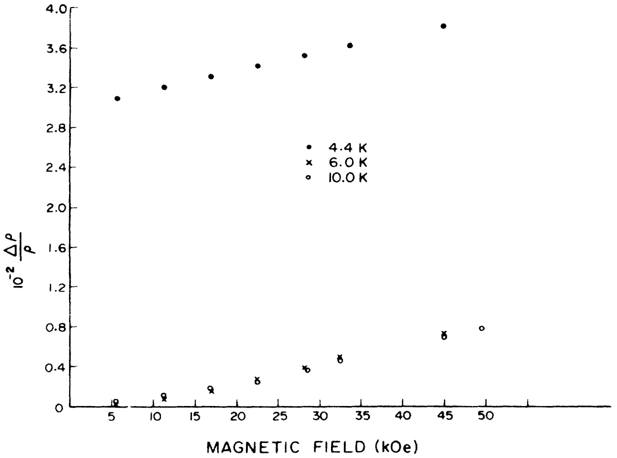

FIG. 6. Variation of longitudinal magnetoresistance $\Delta\rho/\rho$ of V_3Pt with field.

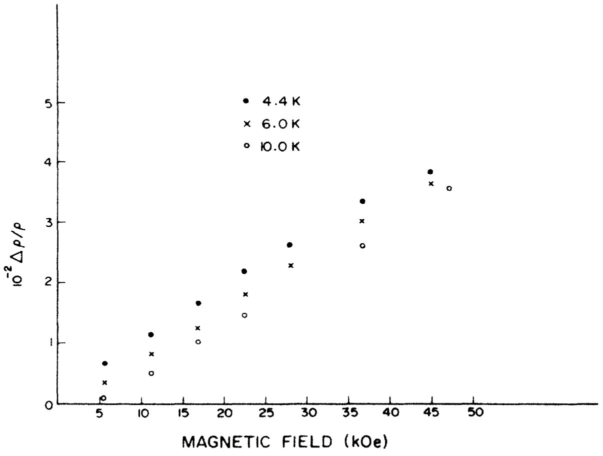

FIG. 7. Variation of longitudinal magnetoresistance $\Delta\rho/\rho$ of V_3Au with field.

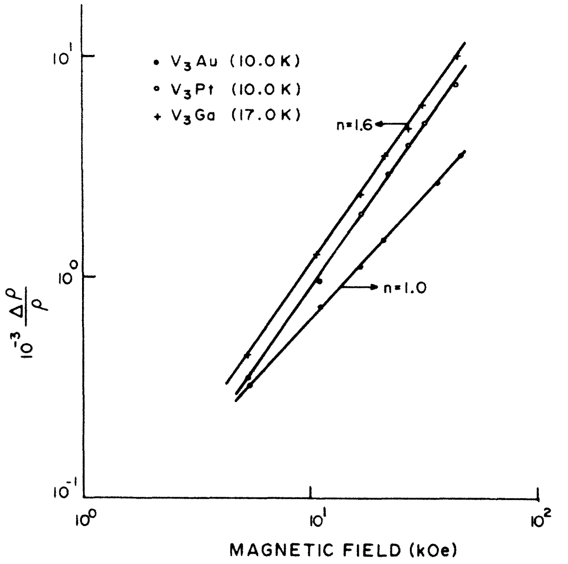

FIG. 8. Field dependences of $\Delta\rho/\rho$ for V_3X (X = Ga, Pt, and Au) compounds.

dence for their model. However, a direct observation of the influence of field on A in simple metals is difficult because of the fact that the electron-phonon interaction is much larger than the electron-electron interaction at these temperatures. However, Kaveh and Wiser have claimed[23] that the T^2 dependence of resistivity observed in $A15$ compounds is due to electron-electron interaction mediated by phonons. They have shown that as T_c decreases (γ decreases), the value of A is also decreased. We know that the application of magnetic field decreases T_c and hence this should decrease A. Therefore we should expect a decrease in the resistivity in applied field to be consistent with their model.

Longitudinal magnetoresistance [$\Delta\rho/\rho$, where $\Delta\rho=\rho(H)-\rho(0)$] of $A15$ V_3X (X = Ga, Au, and Pt) compounds has been measured with a superconducting magnet up to a field of 5 T at various temperatures. It is found to be positive in all cases. The field dependences of the magnetoresistance of V_3Ga ($T_c=14.9$ K) for three different temperatures are shown in Fig. 5. Compared to Ti_3Sb and Nb_3Au,[24] the magnetoresistance shows relatively weaker dependence on field. The large decrease in $\Delta\rho/\rho$ from 15 to 17 K is likely to be due to the presence of superconducting fluctuations.[25] The magnetoresistance increases rapidly with field up to 5 kOe and at this field superconductivity is completely destroyed. Further increase of magnetoresistance is due to the normal state of this compound. Such a dependence is not observed at 17 K because the compound is already in the normal state at zero field. The variation of $\Delta\rho/\rho$ with magnetic field for V_3Pt ($T_c=3.0$ K) at different temperatures is shown in Fig. 6. Similar behavior is observed for V_3Au (Fig. 7) except that one does not see any suppression of superconducting fluctuations in this compound. This could be due to the low T_c (2.0 K) of this compound.

TABLE IV. Magnetoresistance of some $A15$ compounds.

Sample	T_c (K)	L	n	T (K)[a]
V_3Ga[b]	14.50	0.29×10^{-4}	1.6	15.0
V_3Pt[b]	3.00	0.24×10^{-4}	1.6	10.0
V_3Au[b]	2.00	0.59×10^{-4}	1.0	10.0
Ti_3Sb[c]	6.54	0.50×10^{-3}	1.0	4.4
Nb_3Au[c]	11.00	0.31×10^{-3}	1.0	12.0
Nb_3Sb[d]	0.20		2.0	

[a] Temperature at which $\Delta\rho/\rho$ is measured.

[b] This work.

[c] Data taken from Ref. 23.

[d] Data taken from Ref. 24.

The magnetoresistance is fitted to the expression

$$\frac{\rho(H)-\rho(0)}{\rho(0)}=LH^n\,, \tag{7}$$

where L and n are constants. The values of L and n for the three compounds are given in Table IV. The magnetoresistance of all the three alloys is shown in Fig. 8. The magnetoresistance of both V_3Ga and V_3Pt has a $H^{1.6}$ dependence, whereas that of V_3Au shows a linear dependence. However, all the three alloys show a positive magnetoresistance which contradicts the result deduced from the Kaveh and Wiser model. The field dependence of magnetoresistance of V_3Ga and V_3Pt is different from that of Nb_3Au and Ti_3Sb, where it is linear.[24] Although a quadratic field dependence of magnetoresistance was observed before in Nb_3Sb,[26] a linear dependence has not been observed before. Such a linear dependence can perhaps be explained by showing that the magnetoresistance averaged over all orientations of H has a linear field dependence in these polycrystalline samples. However, detailed theoretical analysis of magnetoresistance is not available except in the work of Ziman,[27] who explained the magnetoresistance of polycrystalline copper. Hence, all one can say at this moment is that the low-temperature resistivity of $A15$ compounds may not be due to phonon-mediated electron-

electron scattering as proposed by Kaveh and Wiser. More data on other *A*15 alloys and large inputs from the theorists are needed for a complete understanding of this phenomenon.

V. CONCLUSION

In this paper we have reported the low- and high-temperature (up to 300 K) resistivity behavior of V_3X (X=Ga, Pt, and Au) compounds. $\rho(T)$ of V_3Ga and V_3Au shows a T^2 dependence at low temperatures, whereas that of V_3Pt shows a T^3 behavior in this temperature range. A theoretical understanding of this phenomena is not satisfactory. At high temperatures, $\rho(T)$ of all three compounds can be fitted to the parallel resistor model. There is a need for a general theory to explain the magnetoresistance behavior of *A*15 compounds.

Recently, Gurvitch[28] has suggested that the simultaneous presence of strong coupling (large λ) and disorder leads to a T^2 dependence of resistivity at low temperatures. However, we find that the $\rho(T)$ of V_3Au ($\lambda=0.5$) also shows a T^2 dependence at low temperatures. This result does not seem to agree with the model proposed by Gurvitch.[28]

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