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# Weak localization and electron–electron interaction in disordered $V_{80}Al_{20-x}Fe_x$ alloys at low temperature

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**Abstract**

In this Letter we report on the electrical resistivity and magneto-resistivity of disordered $V_{80}Al_{20-x}Fe_x$ alloys in the temperature range $1.5 \leqslant T \leqslant 300$ K and analyze them in the light of weak localization and electron–electron interaction. The low temperature zero field resistivity obeys a $T^{1/2}$ law, which is explained by electron–electron interaction. The low field magneto-resistivity is described by weak localization theory under strong spin–orbit interaction. The electron–phonon scattering rate obeys a quadratic temperature dependence. This observation is interpreted by the existing theories of electron–phonon interaction.


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*Keywords:* Vanadium alloy; Electron–phonon scattering; Magneto-resistivity; Low temperature

## 1. Introduction

The properties of disordered metals have long been a subject of interest. In the last few decades much theoretical and experimental effort has been made to study the problem of electron transport in a random potential [1–7]. The motion of electrons in disordered systems is one of the most important and fundamental problems in condensed matter physics. Both theoretical and experimental investigations of the low temperature electrical resistivity of disordered electronic systems have led to quantum corrections to the classical Boltzmann contribution during the last few decades. The corrections assume more and more importance as the temperature approaches zero with the accompanying effect of disorder. This non-classical aspect of the carrier transport mechanism has been theoretically interpreted by two distinct phenomena—namely, the electron–electron interaction (EEI) and the weak localization (WL) phenomenon. The electron–electron interaction is less sensitive to the magnetic field and produces a positive magneto-resistance at high magnetic field. Thouless [8] first studied WL from the scaling theory and found that WL behaviour is strongly

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dependent on the dimension of the system. The WL results from the enhanced back scattering probability of the electrons due to the interference by partial electron waves travelling along time reversed electron-path. Constructive interference will occur even in the presence of elastic scattering since this type of scattering does not influence the phase coherence of the electrons. The scattering events, which affect the wavelength of the electronic wave function, are mainly the electron–electron and electron–phonon scattering, which are strongly reduced at low temperature. An externally applied magnetic field suppresses the phase coherence and we have negative magneto-resistance. Later, the theory was extended to take into account other scattering mechanisms namely, the spin–orbit coupling, which produces an antilocalization effect and the result is positive magneto-resistance and the scattering by magnetic impurities, which produces a saturation of the additional resistivity at low temperature. Although EEI and WL introduce temperature dependent corrections to resistivity at low temperature, it is known that in case of three-dimensional disordered metals, the temperature dependent resistivity at zero magnetic fields is dominated by EEI correction and the field dependence in low fields is dominated by the WL corrections. The magneto-resistivity study by WL provides quantitative information regarding dephasing time for inelastic scattering, spin–orbit scattering and spin–spin scattering in respect of the electron wave function. Many theoretical [3,6] and experimental [9–13] works have established that the electron–electron scattering dominates the dephasing process in reduced dimensional systems and its temperature and disorder dependence has been quite well developed. Although, the temperature behaviour of the electron–phonon scattering is well established in pure or clean conductors [14,15], the nature of electron–phonon scattering in disordered metals is still under controversy [16–26]. In this work we want to study the WL and EEI effects in disordered $V_{80}Al_{20-x}Fe_x$ alloys and also study the anomalous temperature behaviour of electron–phonon scattering at low temperature.

## 2. Experimental method

$V_{80}Al_{20-x}Fe_x$ alloys were melted in an arc-melting furnace with $x = 0$, 1 and 2. The melting procedure involved repeated melting and solidification of the alloy in the furnace after physical mixing of spec-pure vanadium, aluminium and iron in suitable proportions. To ensure homogenisation of composition in the alloy ingots, the same were annealed at 800 °C for a period of 50 to 170 hours. The dimension of the sample for resistivity measurement was $0.2 \times 0.2 \times 10\ \text{mm}^3$. Platinum electrodes were joined with the samples for electrical connection by spot welding. The standard four-probe technique was used for measurement of resistivity. Low temperature measurement was performed in a $^4$He cryostat. Calibrated carbon glass and $RuO_2$ thermometer were used as sensors to monitor the temperature of the specimen. To avoid the harmful effect of joule heating of the electrons, low measurement current was applied. Similarly with a view to minimizing the contribution from the many body EEI effect, a small magnetic field was applied while measuring the magneto-resistance. Free electron model [27] was applied to find out the values of the Fermi wave vector $K_F$, which is given by the relation $K_F = \frac{3.63}{(r_s/a_0)}$ Å, where $a_0$ is the Bohr radius and $r_s$ is the volume of a sphere whose volume is equal to the volume per conduction electron. The electron elastic mean free path ($l_e$) was determined from the relation $l_e = \frac{3\pi^2\hbar}{(K^2 e^2 \rho_0)}$, where $\rho_0$ (at 10 K) is the resistivity due to impurities. The Einstein relation $\frac{1}{\rho_0} = \frac{De^2N(0)}{(1+\lambda)}$, was employed to determine the values of the electron diffusion coefficient. Here $\rho_0$ is the measured resistivity, $N(0)$ is the density of states at Fermi level obtained from specific heat measurement $\gamma T = (\pi^2/3)K_B^2 N(0)$, for vanadium aluminium alloys. A value of 0.46 was used for the electron–phonon coupling constant $\lambda$ [28]. By utilising these values, the expression for diffusion coefficient turns out to be $D = 229/\rho_0\ \text{cm}^2/\text{s}$, $\rho_0$ being in $\mu\Omega\,\text{cm}$ [29]. Table 1 displays the values of $l_e$, $K_F l_e$ and $D$ for different samples.

## 3. Results and discussion

We have measured the electrical resistivity of the disordered polycrystalline $V_{80}Al_{20-x}Fe_x$ alloys both in the absence as well as in the presence of the magnetic field ($B < 1$ Tesla) in the temperature range $1.5 \leqslant T \leqslant 300$ K. The values of resistivity at 10 K and resistivity ratio are given in Table 1. Fig. 1 displays the variation of the electrical resistivity with temperature for different samples. It is apparent from Fig. 1

Table 1
Values of relevant physical parameters for disordered $V_{80}Al_{20-x}Fe_x$ alloys, $\rho_0$ and $\rho(300\ \mathrm{K})$ are the resistivity at 10 and 300 K, respectively, $l_e$ is the mean free path, $D$ is the electron diffusion coefficient, $K_F$ is the Fermi wave vector, $T_{min}$ is the temperature at which resistivity is minimum, $\alpha$ is the coefficient of $T^{1/2}$ variation of resistivity, $\tau_{so}^{-1}$ is the spin–orbit scattering rate and $\tau_{\phi}^{-1}(10\ \mathrm{K})$ is the dephasing scattering rate at 10 K, $\tau_0^{-1}$ is temperature independent dephasing time, $A_{e\text{-}ph}$ is the strength of electron–phonon coupling, $p$ is the exponent of temperature for $\tau_{e\text{-}ph}^{-1}$ and $\tau_{e\text{-}ph}^{-1}$ is the electron–phonon scattering rate calculated from Eq. (5)

| Parameters | $V_{80}Al_{20}$ | $V_{80}Al_{19}Fe_1$ | $V_{80}Al_{18}Fe_2$ |
|---|---|---|---|
| $\rho_0$ (μΩ cm) | 148 | 167 | 180 |
| $\rho(300\ \mathrm{K})/\rho_0$ | 1.017 | 1.024 | 1.039 |
| $l_e$ (Å) | 2.43 | 2.15 | 2.00 |
| $D$ ($\mathrm{cm}^2/\mathrm{s}$) | 1.55 | 1.37 | 1.27 |
| $K_F l_e$ | 4.47 | 3.96 | 3.68 |
| $T_{min}$ (K) | 62.0 | 57.5 | 37.5 |
| $\alpha$ ($\mu\Omega^{-1}\,\mathrm{cm}^{-1}\,\mathrm{K}^{-1/2}$) | $4.70\times10^{-6}$ | $3.76\times10^{-6}$ | $3.15\times10^{-6}$ |
| $\tau_{so}^{-1}$ ($\mathrm{s}^{-1}$) | $8.051\times10^{12}$ | $7.443\times10^{12}$ | $7.112\times10^{12}$ |
| $\tau_{\phi}^{-1}$ ($\mathrm{s}^{-1}$) | $1.239\times10^{11}$ | $1.018\times10^{11}$ | $0.896\times10^{11}$ |
| $\tau_0^{-1}$ ($\mathrm{s}^{-1}$) | $4.874\times10^{10}$ | $2.205\times10^{10}$ | $1.918\times10^{10}$ |
| $p$ | 2.12 | 2.04 | 1.99 |
| $A_{e\text{-}ph}$ ($\mathrm{s}^{-1}\,\mathrm{K}^{-p}$) | $6.508\times10^{8}$ | $7.639\times10^{8}$ | $7.491\times10^{8}$ |
| $\tau_{e\text{-}ph}^{-1}$ ($\mathrm{s}^{-1}$) (theor.) | $2.681\times10^{11}$ | $3.038\times10^{11}$ | $3.268\times10^{11}$ |

that the resistivity of the samples follows a decreasing trend with decreasing temperature touching a minimum at $T = T_{min}$. Further lowering of the temperature ($T < T_{min}$) produces an anomalous behaviour in resistivity property of the disordered alloys by imparting an increasing trend to the resistivity. The values of $T_{min}$ for different samples are listed in Table 1. We have explained this anomaly in resistivity behaviour of such disordered solid at low temperature ($T < T_{min}$) by electron–electron interaction (EEI), weak localization (WL) and Kondo type scattering phenomenon. Theoretically, the effects of EEI in three dimensions cause a resistivity rise at low temperature given by $\frac{\Delta\rho(T)}{\rho_0^2} = \alpha T^{1/2}$ [30,31], where $\alpha$ is a constant and given by the relation

$$\alpha = -\frac{1.3e^2}{4\pi^2\hbar}\left[\frac{4}{3} - \frac{3F}{2}\right]\sqrt{\frac{k_B}{2\hbar D}}, \tag{1}$$

where $k_B$ is the Boltzmann constant, $D$ is the diffusion constant, $\hbar$ is Planck's constant divided by $2\pi$, e is the electronic charge and $F$ is a screening factor averaged over the Fermi surface.

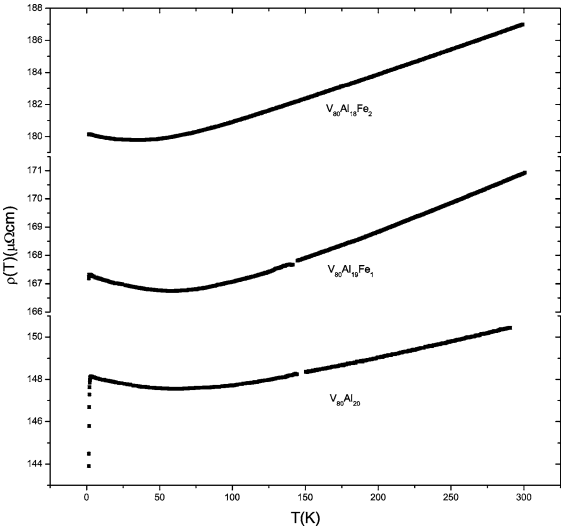


Fig. 1. Variation of electrical resistivity with temperature of different disordered $V_{80}Al_{20-x}Fe_x$ alloys.

A considerable effect of interference between scattered partial waves becomes discernible at low temperature due to the movement of electrons between two scattering events. Under such circumstances, the effect of weak localization assumes the dominating role to influence the resistivity behaviour of disordered metals [32–34] and the temperature dependent part of the resistivity can be expressed as $\frac{\Delta\rho(T)}{\rho_0^2} = \beta T^{p/2}$, where $p$ is an exponent of inelastic scattering time $\tau_i$, which is proportional to $T^p$ and $\beta$ is a constant.

The Kondo type scattering [35] phenomenon also contributes to resistivity by which the resistivity increases with decreasing temperature at low temperature region and the resistivity obeys the relationship $\frac{\Delta\rho(T)}{\rho_0^2} = \eta \ln T$, where $\eta$ is a constant. We may, therefore, express the rise in resistivity at low temperature by combining the effects due to all these three phenomena by the following relationship:

$$\frac{\Delta\rho(T)}{\rho_0^2} = \alpha T^{1/2} + \beta T^{p/2} + \eta \ln T. \tag{2}$$

With a view to understanding the true mechanism in the electron transport in such disordered alloys, we have fitted the experimental data with Eq. (2) taking different constants as fitting parameters. It is found that the experimental data is amenable to produce a good fit with the $T^{1/2}$ but not with $\ln T$ variation in the experimental temperature range of 1.5 K $\leqslant T \leqslant$

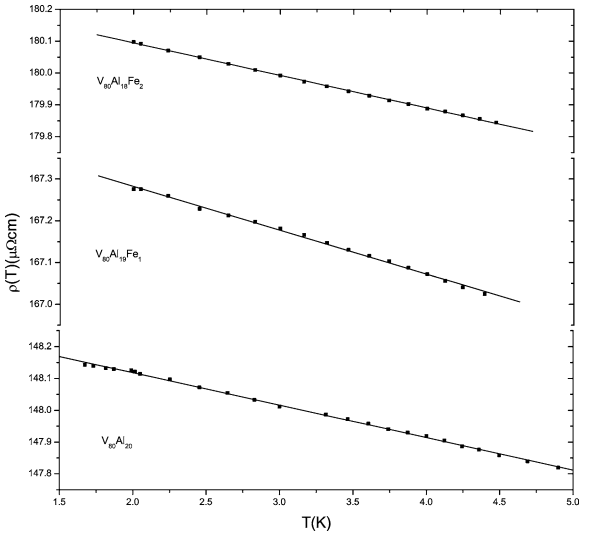


Fig. 2. Electrical resistivity variation as a function of $T^{1/2}$ for different disordered $V_{80}Al_{20-x}Fe_x$ alloys.

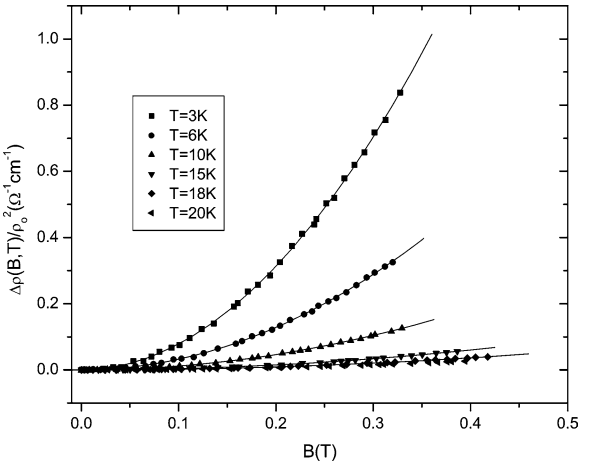


Fig. 3. The variation of the magneto-resistivity with magnetic field at different constant temperature of $V_{80}Al_{19}Fe_1$ alloy. The points are the experimental data and the solid lines are the theoretical predictions from Eq. (3).

$T_{\min}$. This rules out any effect of Kondo type scattering to account for rise in resistivity below $T_{\min}$. In Fig. 2, points represent the experimental data and solid lines show the fitted values obtained from the relation $\frac{\Delta\rho(T)}{\rho_0^2} = \alpha T^{1/2}$. The values of the fitting parameter $\alpha$ for different samples have been listed in Table 1. It has been observed that the two effects namely, the WL and EEI effects are the major contributing factors toward resistivity correction in disordered conductors. However, the temperature dependence of resistivity in three-dimensional disordered metals, in absence of a magnetic field is dominated by the EEI correction. Therefore, it may be inferred that the $T^{1/2}$ dependent resistivity-rise with decreasing temperature in disordered $V_{80}Al_{20-x}Fe_x$ alloys is due essentially to the EEI effects.

While measuring the magneto-resistance, the magnetic field was kept well below 1 Tesla so as to minimize the effect of any contribution arising from many body electron–electron interaction. The positive values of magneto-resistance for all the samples confirm the existence of strong spin–orbit scattering effects even if the constituents are of lower atomic numbers [36]. A very similar finding was recorded in the study of highly resistive crystalline $Ni_xSi_{1-x}$ films [37]. The alloys under investigation being highly resistive are susceptible to strong electron-elastic scattering and show strong spin–orbit scattering.

It is well known that quantitative information on impure metals for the electron dephasing scattering time can be obtained from the measurements of the magneto-resistance due to weak localization effects along with contribution from superconducting fluctuation. This therefore, enables us to introduce the effect of three-dimensional weak localization along with superconducting fluctuation correction [38–40] in the low field region to interpret the magneto-resistance data. In order to calculate the different scattering fields such as the electron dephasing scattering field ($B_\phi$) and the spin–orbit scattering field ($B_{so}$), we have fitted the experimental magneto-resistance data with Eq. (2) using $B_\phi$ and $B_{so}$ as fitting parameters for a particular temperature. Fig. 3 shows the variation of the magneto-resistance with magnetic field for $V_{80}Al_{19}Fe_1$ sample in which the points represent the experimental data and the solid lines display the theoretically best fitted values obtained by using Eq. (3).

$$\frac{\Delta\rho(B,T)}{\rho_0^2} = \frac{e^2}{2\pi^2\hbar}\sqrt{\frac{eB}{\hbar}}\left[\frac{1}{2}f_3\left(\frac{B}{B_\phi}\right) - \frac{3}{2}f_3\left(\frac{B}{B_\phi + \frac{4}{3}B_{so}}\right) - \beta(T)f_3\left(\frac{B}{B_\phi}\right)\right], \quad (3)$$

where the function $f_3(x)$ has already been defined in Ref. [41] and $\beta(T)$ is the superconducting fluctuation parameter [39]. The different scattering times have been calculated from the best fitted values at $B_\phi$ and $B_{so}$ by using the relation $\tau_x = \frac{\hbar}{4eDB_x}$ where $x = \phi$ for electron dephasing scattering and $x = so$ for spin–orbit scattering. The calculated values of $\tau_{so}$ and $\tau_\phi$ show that the spin–orbit scattering rate is independent of temperature and is higher than the electron dephasing scattering rate, i.e., $\tau_{so}^{-1} > \tau_\phi^{-1}$. The values of $\tau_{so}^{-1}$ and $\tau_\phi^{-1}$ (10 K) are listed in Table 1. $\tau_\phi$ possesses two components, one of which is temperature independent ($\tau_0$), and the other one which is temperature dependent ($\tau_i$), i.e., inelastic scattering time. This is given by

$$\tau_\phi^{-1} = \tau_0^{-1} + \tau_i^{-1} = \tau_0^{-1} + \tau_{e\text{-}ph}^{-1}. \quad (4)$$

The electron–phonon scattering ($\tau_{e\text{-}ph}^{-1}$) and the electron–electron scattering ($\tau_{e\text{-}e}^{-1}$) are the two main mechanisms, which are responsible for inelastic scattering. It is the electron–electron scattering that dominates in reduced dimensional systems [42,43], but in case of such disordered three-dimensional alloys, the inelastic scattering is dominated by electron–phonon scattering [18,44]. In accordance with the general theoretical prediction the electron–phonon scattering rate may be expressed as $\tau_{e\text{-}ph}^{-1}(T) \sim A_{e\text{-}ph}T^p$ taking $p = 3$ for clean systems in case of three-dimensional specimens. The variation of $\tau_\phi^{-1}$ with temperature for $V_{80}Al_{19}Fe_1$ alloy is shown in Fig. 4 in which the symbols represent the experimental data whereas the solid curve is the least square fit to Eq. (4) with $\tau_0$, $A_{e\text{-}ph}$ and $p$ as free parameters. The best fitted value of $\tau_0 = 4.535 \times 10^{-11}$ s, $A_{e\text{-}ph} = 7.639 \times 10^8$ s$^{-1}$ K$^{-p}$ and $p = 2.04$. The dotted and short dashed curves show the least square fits to Eq. (4) with fixed values of $p$ as 3 and 4, respectively, although the parameters $\tau_0$ and $A_{e\text{-}ph}$ were allowed to vary. It is evident from the Fig. 4 that the temperature dependent part of the measured $\tau_\phi^{-1}$ shows only a quadratic temperature dependence. The variation of $\tau_\phi$ for different samples over the temperature range of 2 to 20 K has been shown in Fig. 5. The points indicate the experimental data and the solid lines indicate the best fitted values employing Eq. (4) with adjusting parameters $\tau_0$, $A_{e\text{-}ph}$ and $p$. The values of our best fitted adjusting parameters are $\tau_0 = (5.214\text{–}2.052) \times 10^{11}$ s,

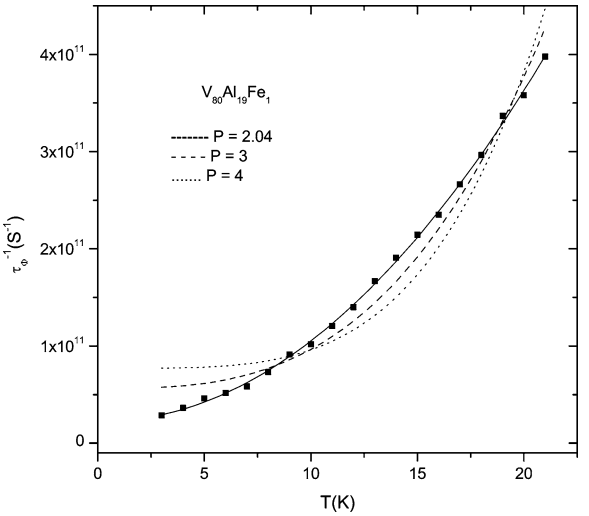


Fig. 4. Electron dephasing rate $\tau_\phi^{-1}(T)$ as a function of temperature for the $V_{80}Al_{19}Fe_1$ alloy. The solid, dashed and dotted curves are least square fit to Eq. (4) with the exponent of temperature $p = 2.04$, 3 and 4, respectively.

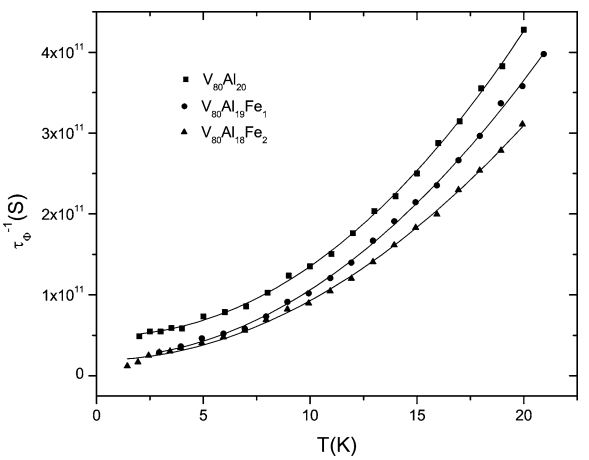


Fig. 5. Electron dephasing rate $\tau_\phi^{-1}(T)$ as a function of temperature for the $V_{80}Al_{20-x}Fe_x$ alloys. The solid curves are least square fit to Eq. (4).

$A_{e\text{-}ph} = (6.508\text{–}7.639) \times 10^8$ s$^{-1}$ K$^{-p}$ and $p = 1.99$ to 2.12. A large number of authors have proposed different theories for the electron–phonon interaction in impure metals. Bergmann and Takayama, to name a few, have proposed models for electron–phonon interaction in dirty metals [16,17]. According to them, the impurities act as additional source for electron–phonon scattering process while participating in lat-

tice oscillation particularly with low-energy transfer. The Eliashberg function, $\alpha_{\rm ep}^2 F(\omega) \sim \omega$, predicted by them depends linearly on the phonon frequency $\omega$ in the low-$\omega$ regime. The function has been used by many authors in their experimental verification in electron tunneling measurements that leads to $T^2$ dependence of $\tau_{\rm ep}^{-1}$ [44]. However, later detailed microscopic study confirmed the prediction of Eliashberg function to be incorrect [18–22,45]. A satisfactory explanation was put forward by Rammer and Schmid [18] who worked out the problem by considering impurity atoms to be moving in phase with other lattice atoms that leads to weakening of $\tau_{\rm ep}^{-1}$ assuming the order of $(q_{\rm ph}l)\tau_{\rm ep,0}^{-1}$, where $\tau_{\rm ep,0}^{-1} \sim T^3$ is the electron–phonon scattering in clean metal. Rammer–Schmid theory predicted that $\tau_{\rm ep}^{-1}$ should follow a $T^4$ at low temperatures. Reizer, Sergeev and Belitz [19–21] have independently confirmed this theoretical prediction and has found wide acceptance by the theoretical investigators. The authors worked out the value of $p$ which turned out to be 2 for $\tau_{\rm ep}^{-1}$ in impure $V_{80}Al_{20-x}Fe_x$ alloy system which is not in agreement with Rammer–Schmid theory that predicts the value of $p$ to be 4.

Sergeev and Mitin [45] however, in contrast to all earlier theories, took into account both the static and vibrating random potentials in their proposed mechanism. They have observed that the event of complete dragging of random scattering potentials by phonons makes the effective electron–phonon interaction decrease due to disorder, resulting in $\tau_{\rm ep}^{-1} \sim T^4$ at low temperatures. This confirms the Rammer–Schmid theory about dirty metals. Sergeev and Mitin correctly surmised that in real metallic disordered systems, phonons would not be always capable of dragging the imperfections completely. They further observed that such incomplete dragging would cause a non-monotonic temperature and disorder behaviour of the electron–phonon interaction and concluded that interaction between electron and transverse phonons would be more effective than the interaction between electron and longitudinal phonons and result in the anomalous $T^2$ dependence of $\tau_{\rm ep}^{-1}$ in the dirty limit $q_{\rm ph}l \ll 1$ and in the temperature $T < \frac{\hbar u_t}{K_B l_{\rm e}}$. The samples investigated by the authors satisfied the condition $T < \frac{\hbar u_t}{K_B l_{\rm e}}$. Therefore, the electron–phonon scattering rate [22,45] has been calculated to illustrate our results by using the following formula, which conforms to the aforesaid condition:

$$\tau_{\rm e\text{-}ph}^{-1} = \frac{\pi^2 k_{\rm B}^2 \hbar^2 K_{\rm F}^2 (1+\lambda) k(1-k)}{6m^2 \rho u_t^3 l_{\rm e} e^2 \rho_0 D} T^2, \tag{5}$$

where $\rho$ is the density and $u_t$ is the transverse velocity and $k$ is a constant. Taking the values of $\rho = 4.56 \times 10^3$ kg/m$^3$, $u_t = 3.10 \times 10^3$ m/s, $\lambda = 0.46$, $K_{\rm F} = 1.84 \times 10^{10}$ m$^{-1}$ for $V_{80}Al_{20-x}Fe_x$ samples with $k = 0.5$, the calculated values of $\tau_{\rm e\text{-}ph}^{-1}$ at 10 K are $(2.68–3.27) \times 10^{11}$ s$^{-1}$ whereas the experimental values are $(7.05–7.97) \times 10^{10}$ s$^{-1}$. It is therefore, evident that the magnitude of the theoretical values is about four times greater than that of the values obtained experimentally even if the quadratic temperature dependence of $\tau_{\rm e\text{-}ph}^{-1}$ for the investigated samples obeys the above theoretical prediction. Therefore, it may be concluded that this observation cannot be fully understood in terms of existing electron–phonon interaction theory for impure metals. A clear understanding of this requires further detailed investigation.

For our greater concern over mechanism of the electron–phonon scattering in the dirty limit, it is now necessary to examine whether the disordered criterion $q_{\rm ph}l_{\rm e} \leqslant 1$ is satisfied in the present study. Taking $V_{\rm s} \approx 4.10 \times 10^3$ m/s for high resistive $V_{80}Al_{20-x}Fe_x$ alloys [29], we obtain $q_{\rm ph}(T)l_{\rm e} = (0.0064–0.0103)T$, where $T$ is in Kelvin. It is noticeable that the high values of resistivity $\rho_0$, has rendered the electron mean free path to be very short in these alloys, which has resulted in a very small magnitude of $q_{\rm ph}l_{\rm e}$. Therefore, the dirty limit criterion of $q_{\rm ph}l_{\rm e} < 1$ is well satisfied for the electron–phonon processes in the investigated samples even at the highest measurement temperatures of ∼20 K.

The electron dephasing lengths $L_\phi = (D\tau_\phi)^{1/2}$ for the $V_{80}Al_{20-x}Fe_x$ alloy systems have been determined by employing the measured values of $\tau_\phi(T)$. We find that $L_\phi(T)$ varies from about 190 Å to 1034 Å as the measurement temperature decreases from 20 to 1.5 K. Therefore, every alloy sample studied in this work lies well within the three dimensional regime. This lends justification to our using the three-dimensional weak localization theory to describe the experimental magneto-resistances.

## 4. Conclusion

In this work we have studied electrical resistivity and magneto-resistivity of three-dimensional disordered $V_{100-x}Al_{x-y}Fe_y$ alloys in the temperature range $1.5 \leqslant T \leqslant 300$ K. A minimum on the resistivity versus temperatures curve exists at $T = T_{\min}$. At low temperature ($1.5 \leqslant T \leqslant T_m$) the zero field resistivity obeys the $T^{1/2}$ law indicating the prominence of electron–electron interaction. The magneto-resistivity of all the alloys is positive and well described by the WL theory under strong spin–orbit scattering at small magnetic field. By analyzing the magneto-resistivity data, we have calculated the electron–phonon scattering time ($\tau_{\text{e-ph}}$), which obeys a quadratic temperature dependence, $\tau_{\text{e-ph}}^{-1} \propto T^2$. Such quadratic temperature behaviour of electron–phonon scattering time is explained by existing theory but its magnitude does not satisfactorily match the theoretically predicted value. Therefore, our observed data on electron–phonon scattering failed to give an exact agreement with the existing theory.

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## References

[1] H. Suhl, M.B. Maple (Eds.), Superconductivity in $d$- and $f$-Band Metals, Academic Press, New York, 1980.
[2] W. Buckel, W. Weber (Eds.), Superconductivity in $d$- and $f$-Band Metals, Kernforschungszentrum, Karlsruhe GmbH, Karlsruhe, 1982.
[3] B.L. Altshuler, A.G. Arnov, in: A.L. Efros, M. Pollok (Eds.), Electron–Electron Interactions in Disordered Systems, Elsevier, Amsterdam, 1985.
[4] J.H. Mooij, Phys. Status Solidi A 17 (1973) 521.
[5] G. Bergmann, Phys. Rep. 107 (1984) 1.
[6] P.A. Lee, T.V. Ramakrishnan, Rev. Mod. Phys. 57 (1985) 287.
[7] C.C. Tsuei, Phys. Rev. Lett. 57 (1986) 1943.
[8] D.J. Thouless, Phys. Rev. Lett. 39 (1977) 116.
[9] A.K. Meikap, S.K. De, S. Chatterjee, Phys. Rev. B 49 (1994) 1054.
[10] G. Bergmann, Phys. Rev. Lett. 48 (1982) 1048.
[11] E. White, R.C. Dynes, J.P. Garno, Phys. Rev. B 29 (1984) 3694.
[12] A.K. Meikap, A.R. Jana, S.K. De, S. Chatterjee, J. Low Temp. Phys. 85 (1991) 295.
[13] P. Santhanam, S. Wind, D.F. Prober, Phys. Rev. B 35 (1987) 3188.
[14] M.Yu. Reizer, Phys. Rev. B 40 (1989) 5411.
[15] M.L. Roukes, M.R. Freeman, R.S. Germain, R.C. Richardson, M.B. Ketchen, Phys. Rev. Lett. 55 (1985) 422.
[16] G. Bergmann, Phys. Rev. B 3 (1971) 3797.
[17] T. Takayama, Z. Phys. 263 (1973) 329.
[18] J. Rammer, A. Schmid, Phys. Rev. B 34 (1986) 1352.
[19] M.Yu. Reizer, A.V. Sergeev, Sov. Phys. JETP 63 (1986) 616, Zh. Eksp. Teor. Fiz. 90 (1986) 1056 (in Russian).
[20] A.V. Sergeev, M.Yu. Reizer, Int. J. Mod. Phys. B 10 (1996) 635.
[21] D. Belitz, Phys. Rev. B 36 (1987) 2513.
[22] A. Sergeev, V. Mitin, Phys. Rev. B 61 (2000) 6041.
[23] J.J. Lin, C.Y. Wu, Europhys. Lett. 29 (1995) 141.
[24] K.P. Peters, G. Bergmann, J. Phys. Soc. Jpn. 54 (1985) 3478.
[25] J.F. DiTusa, K. Lin, M. Park, M.S. Isaacson, J.M. Parpia, Phys. Rev. Lett. 68 (1992) 1156.
[26] C.Y. Wu, W.B. Jian, J.J. Lin, Phys. Rev. B 57 (1998) 11232.
[27] C. Kittel, Introduction to Solid State Physics, Wiley, New York, 1986.
[28] W.L. McMillan, Phys. Rev. 167 (1968) 331.
[29] A.K. Meikap, Y.Y. Chen, J.J. Lin, Phys. Rev. B. 2004, in press.
[30] B.L. Al'tshuler, A.A. Aronov, Sov. Phys. JETP 50 (1979) 968, Zh. Eksp. Teor. Fiz. 77 (1979) 2028 (in Russian).
[31] M. Kavch, N.F. Mott, J. Phys. C: Solid State Phys. 15 (1982) L707.
[32] A. Sahnoune, J.O. Strom-Olsen, Phys. Rev. B 29 (1989) 7561.
[33] M.A. Howson, D. Greig, J. Phys. F 16 (1986) 989.
[34] M.A. Howson, J. Phys. F 14 (1984) L25.
[35] J. Kondo, Prog. Theor. Phys. 32 (1964) 37.
[36] A. Abrikosov, L.P. Gorkov, Sov. Phys. JETP 15 (1962) 752, Zh. Eksp. Teor. Fiz. 42 (1962) 1088 (in Russian).
[37] C. Segal, A. Gladkikh, M. Pilosof, H. Behar, M. Witcomb, R. Rosenbaum, J. Phys.: Condens. Matter 10 (1998) 123.
[38] W. Brenig, M.C. Chang, E. Abrahams, P. Wolfle, Phys. Rev. B 31 (1985) 7001.
[39] A.I. Larkin, JETP Lett. 31 (1980) 219, Pis'ma Zh. Eksp. Teor. Fiz. 31 (1980) 239 (in Russian).
[40] H. Fukuyama, K. Hoshino, J. Phys. Soc. Jpn. 50 (1981) 2131.
[41] D.V. Baxter, R. Richter, M.L. Trudeau, R.W. Cochrane, J.O. Strom-Olsen, J. Physique 50 (1989) 1673.
[42] B.L. Al'tshuler, A.G. Aronov, M.E. Gershenson, Yu.V. Sharvin, Sov. Sci. Rev. A 9 (1987) 223.
[43] M.E. Gershenson, Ann. Phys. (Berlin) 8 (1999) 559.
[44] G. Bergmann, W. Wei, Y. Zou, R.M. Mueller, Phys. Rev. B 41 (1990) 7386.
[45] A. Sergeev, V. Mitin, Superlattices Microstruct. 27 (2000) 499; A. Sergeev, V. Mitin, Europhys. Lett. 51 (2000) 641.