Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

A Brief Review on the Electrical Resistivity Of Aluminium Alloy and its Nanoparticles at Low Temperature

Inzamam Khalid[1,a]

[1]Department of Physics, Government College University, Lahore

[a]Email: inzamamkhalid16@gmail.com

Abstract. *The objective of this review article is to study the resistivity of aluminium alloy at low temperatures. Various articles have been thoroughly studied for this review. Alloys that contain Al as dominant metal are termed as Al alloys. The first conventional Al alloy was prepared A6160 whose major constituents are Si and Mg. Al metal in its pure form has very high electrical conductivity but it is soft. Foils and conductor cables are made of Al. For advanced applications, Al is alloyed. The review has briefly explained the physical background of electrical resistivity and analysis of chosen material, aluminium alloy. Furthermore it has also discussed the resistivity of nanoparticles of Aluminium alloy.*

Keywords: Aluminium alloys, electrical resistivity, temperature, impurity

1. Introduction

Materials behaviour is mainly characterised by the nature of their constituents. The evolved Physical and nonphysical features are then attributed to the components and vary by external factors such as pressure and temperature, in general. Specified electrical properties also depend upon the structure of the material. Due to that, conducting, with low resistivity, materials are used to supply electric current to long resistance. While in some cases materials with high resistivity applied in different appliances e.g. electric heater, iron filament, etc. electrical and electronic systems use electrical resistance as the key parameter for the selection of materials. The right selection of material is based upon the required application. Power distribution systems rely on electrical resistivity to assess transmission lines, earth grounding, and soil material. Electrical resistivity is a manipulating variable function of temperature.

Electrical resistivity can be measured by using various methods and models. The shape of the sample and contact resistance defines which method is suitable for precision measurements. The resistivity of high resistive samples can be measured by using two probes methods (ohm metre or voltmeter – ammeter measurements) [15]. Four probes methods can be used for the measurement of resistivity of materials those who have low resistance and single crystals. The resistivity of the pellets and bulky samples can be measured by using Montgomery, van der Pauw, and Smith techniques. These are conventional techniques by which resistivity can be measured but other techniques which use modern technology analyse the resistivity. Electrical resistivity is essential for the applications of metals, alloys and their nanoparticles, and a thorough understanding of their electrical resistivity is much needed. In many electrical applications we utilise in our daily lives, the electrical behaviour of a material can be as, and sometimes more, important than the mechanical properties. The electrical resistivity of aluminium alloy is of great practical importance especially in applications involving aerospace, automotive, architectural, lithographic, electric, and electronic applications.

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

2. Electrical Resistivity of Aluminium alloy at low temperature

The resistivity of aluminium alloy varies from 0.5-6 μΩ cm as a function of temperature. But it was noticed by C. H. Yin and L. M. Qiu that variation in resistivity is infinitesimally small below 77K temperature [1]. At very low temperatures, especially lower than 20 K resistivity becomes nearly constant of Al alloys. The resistance of different aluminium alloys at low temperature (ranges from ice point to helium temperature) will be (0.18-2.16)×10^{-3} with sample size $5 \times 0.5 \times 90$ $(width \times thickness \times length)$. The resistivity of aluminium alloys at low temperatures is 1000 times more than pure aluminium [2].

Theoretical analysis shows that the cryocooler instrument can be used to study electrical resistivity below 38 K temperature [1]. To achieve a low-temperature environment two-stage cooler is used. By providing constant current the voltage is measured with variation in temperature.

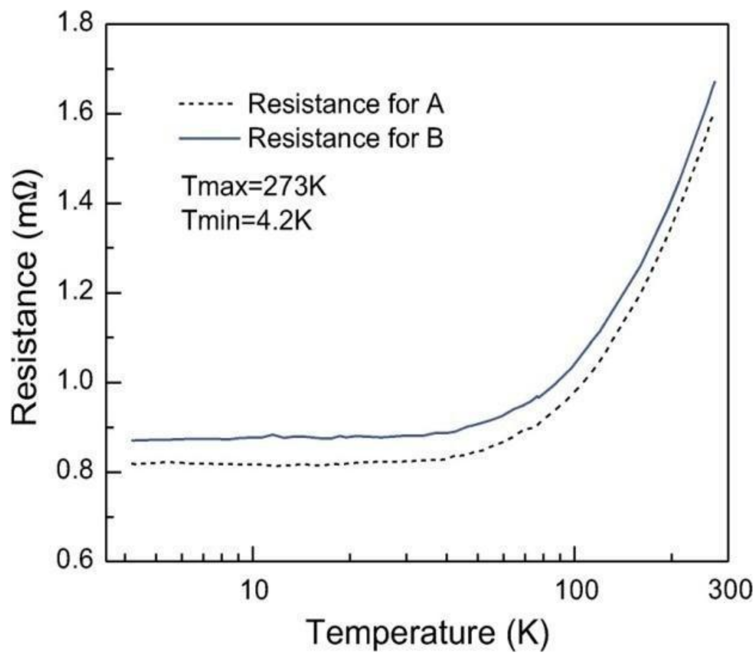

Figure 1. Resistance vs temperature of the cryocooler measurement platform [1].

As the Debye temperature of aluminium is 380 K which concludes that its resistance below 38K nearly constant which can be shown in figure 1. Above 90 K resistance is nearly proportional to temperature. The results can be compared with the Physical Property Measurement System (PPMS) system's results to prove that they are accurate and reliable. Experimental verification of the cryocooler measurement method is performed which shows only 1 %. The resistance of the aluminium alloy is nearly constant between 38 K and 4.20 K which was proposed theoretically and proved experimentally by C. H. Yin and L. M. Qiu[1]. This experiment also gives convenience that if the experimental setup does not allow 4.2 K temperature, for the measurement of resistivity of materials with low-value Residual Resistivity Ratio or Residual Resistance Ratio (RRR) (RRR<10), we can use any temperature between 38 K and 4.20 K.

R. Krsnik (R.K.) and E. Babic (E.B.) measured the resistivity of aluminium alloys within the temperature range 4.2-100 K. By using rapid quenching techniques they obtained samples

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

covering a wide range of concentrations. R.K and E.B proved experimentally that resistivity of impurity is one greater than the highest found. They also founded from these observations that $\rho_{ph} \propto T^3$ so mainly resistivity depends upon impurities in this range [4].

There are more than ten different mechanisms by which we can observe deviation from the conventional resistivity proposed by Matheissen (total resistivity is the sum of resistivity due to pure host (phonon) and resistivity due to impurity concentrations as well) [5]. We can study and specify some mechanism to eliminate the error factor in deviation from Matthiessen's rule (DMR) by alloying Al metal with different alloying elements and different concentrations. There is an ideology behind the anomalous impurity resistivity which says that interferences of phonon and impurity scattering at different temperatures cause deviation from standard impurity scattering values. Aluminium is best for understanding DMR and anomalous impurity resistivity. Caplina.D. and Rizzutoc founded that Al alloys with non-anomalous impurities resistivity at low temperature is given as,

$$\rho(T) = \rho_0 + \rho_{pure}(T) + A(\rho_0)\, T^3 \tag{1}$$

Where, ρ_0 is residual resistivity and $A(\rho_0)$ is a varying function independent of the impurity. There are two theoretical ways by which equation (1) can be defended: one based on “extra electron-phonon scattering processes due to impurities” while the second one “assumes that the impurities are the relaxation time over the Fermi surface” [6]. To minimize the discrepancy between these two models it would be good to modify recent measurements to higher concentration and very low temperature. Although the solid solubility of elements in aluminium is very high, increasing the concentration is difficult due to the formation of Guinier Preston zones (Nanosized coherent pre-precipitates or solute clusters formed during natural ageing and in the early stages of artificial ageing). So the ultrarapid quenching technique is used to prepare high impurity concentration samples and the molten temperature of sample alloys can be varied. The samples prepared by R.K. and E.B. were thin strips having 20-50 μm thickness, $2-4\,mm$ broadness, and $3-5\,cm$long. Concentrations can be determined with electron microscope analysis and the geometrical factor can be estimated from mass, length, and parameter of the lattice of the samples and via residual resistivity ratio. Resistivity can be measured with the help of potentiometric setup with high accuracy up to 10^{-5}.

R.K. and E.B. concluded that there is no variation in impurity resistivity due to variation in temperature a few Kelvin less than the temperature at which resistivity due thermal agitation is detectable. They also noted that different alloys with different residual resistivity showed the same behaviour during the increase in temperature. Temperature dependence is always T^3 at low temperature and above 20^0K resistivity increases faster same as $\rho_{pure}(T)$ but in case of most concentrated alloys where phonon contribution is completely masked by T^3dependence have the same dependence on T^3. These results are according to the prescribed theoretical models (the first model predicts T^3 dependence at low temperature and the second predicts T^3 dependence only at an intermediate temperature and T^5 dependence at very low temperature but R.K. and E.B. did not extend their measurement for T^5 dependence rather only take measurements for the dependence of T^3). To distinguish between these two models we have to consider the dependence of phonon resistivity on residual resistivity [4].

Computational and Experimental Research
in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

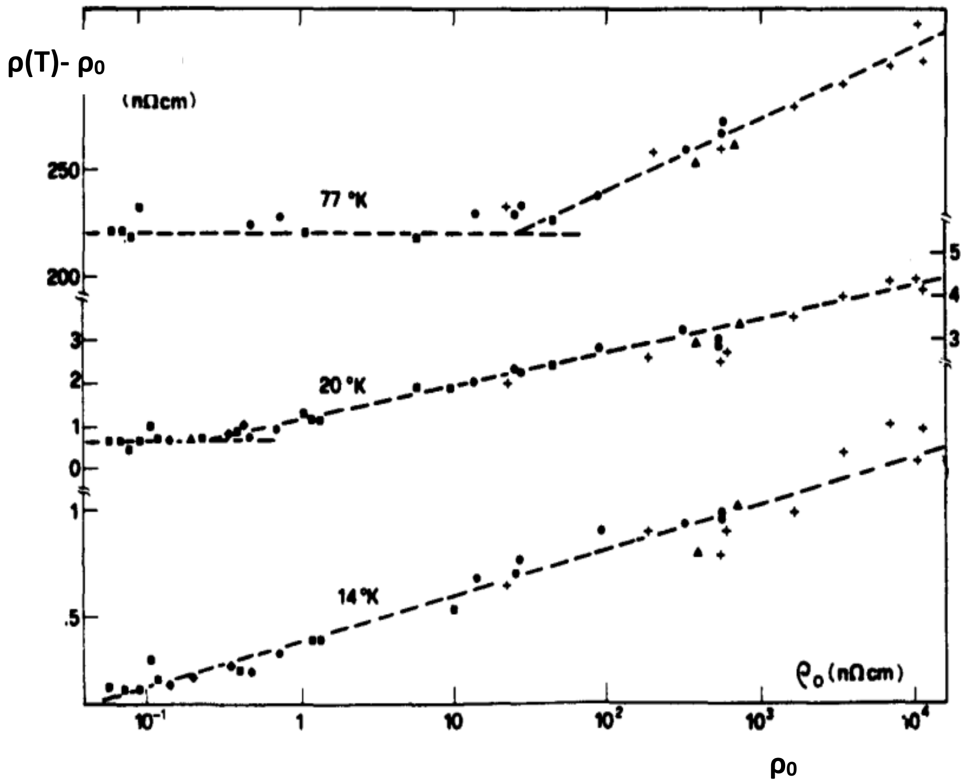

Figure 2. Dependence of phonon resistivity ρ(T)- ρ_0 on impurity resistivity at three fixed temperatures. Data is taken from Senoussi and Campbell [7] measurements and R.K and E.B. measurements.

Although the sample preparation technique was different from R.K and E.B their measurements have good agreement with Senoussi and Campbell measurements. Consequently, they showed that the determination of DMR can get with using concentrated alloys and resistivities of these samples proportional to T^3 up to 0.1 Θ_D (Debye temperature) which depends only log ρ_0 the rapid quenching technique is best for the preparation of samples.

Over a wide range of annealing temperature variation in resistivity is measured during the ageing of aluminium alloy [8]. They took measurements by using a new approach and proposing solubility products for the Q phase in aluminium and identified the contribution to overall resistivity due to precipitates. For studying precipitation in aluminium alloy, an electrical resistivity is a good tool but it is very hard to separate effects due to solute atoms and fine-scale precipitates. When precipitation starts, resistivity increases due to the formation of the solute cluster and keeps growing as precipitants increase. The methodology is also used for the separation of solute from solid solution and is known as resistivity anomaly. Resistivity increases as the function of ageing times and becomes maximum for very long ageing time and then decreases to values below as-quenched resistivity. The effect of ageing can be resolved by distinguishing between resistivity due to solute atoms (described by Matthiessen's rule) and resistivity due to fine-scale precipitates [9]. None theoretical model (e.g. increment in resistivity is due to strong scattering from clusters of solute atoms and reduction in resistivity is due to either increase in cluster's radius more than the mean free path of electrons [9] or to the increasing anisotropy of Bragg scattering from clusters

[11]) could explain anomaly resistivity successfully so experimental calibration is required. Uncertainty in resistivity is due to short quantitative analysis (it is considered that at early stages precipitation is very important while on the other hand effect of precipitates can be ignored when the spacing between clusters is larger than the mean free path of electrons and when spacing is the intermediate effect of a precipitate is less clear).

For the determination of Q phase product solubility and contribution of precipitate resistivity alloy solution prepared and treated at 560 ^{0}C, quenched in water, and for immediate ageing treated with temperature in a range of 200-560 ^{0}C for 1 h. To avoid temperature effects all the measurements were taken by immersing specimens in liquid nitrogen (77 K). Measurements elaborated that initially resistivity increases with increasing ageing temperature and after 350 ^{0}C the process is reversed and a plateau in resistivity is gained at 300 ^{0}C (plateau resistivity increases with temperature). So resistivity will not be affected by precipitates at higher temperatures (due to coarse structure) and the value of plateau resistivity represents the equilibrium condition. While for low-temperature precipitate resistivity is taken into account because plateau resistivity is not gained. So Matthiessen's rule can be moulded according to the above analysis as,

$$\rho = \rho_{pure}(T) + \sum_i \quad \rho_i C_i + \rho_{ppt} \tag{2}$$

Where $\rho_{pure}(T)$ is phonon resistivity due to thermal agitation, ρ_i is resistivity due to specific solute atoms and C_i concentration of specific solute, and ρ_{ppt} resistivity due to the formation of clusters. From plateau resistivity concentrations of precipitates can be measured and by using these concentration solubility products of Q precipitate can be measured.

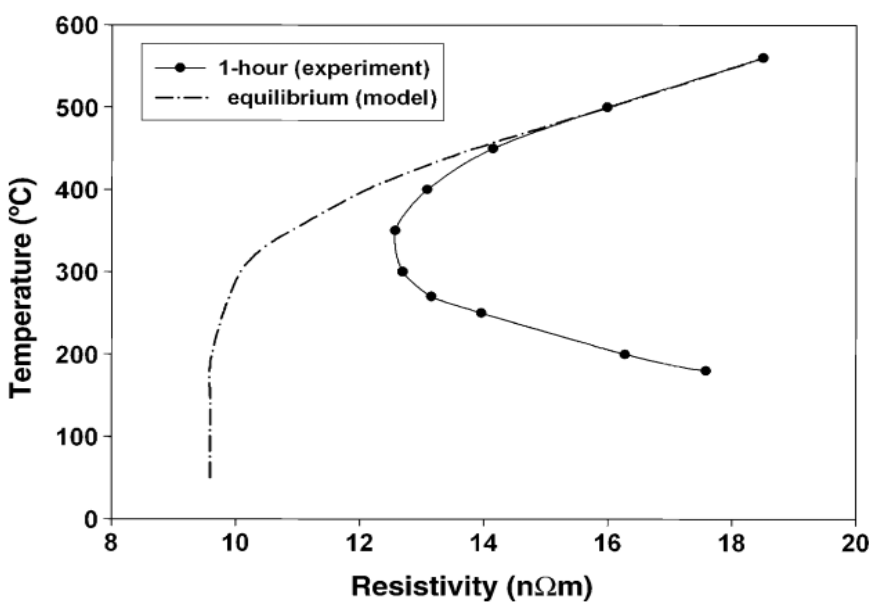

Figure 3. A comparison between experimental and equilibrium values [8]

From figure 3 we can see that when the ageing temperature in the range of 450-560 ^{0}C the experimental and equilibrium values coincide but when decrement in temperature takes place

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

deviation of equilibrium values can be seen towards higher resistivities. The reason behind this deviation is due to the effect of precipitate resistivity and precipitate resistivity (depending on the separation between precipitates) can be calculated as,

$$\rho_{ppt} = \frac{12}{L^{1/2}} \tag{3}$$

where L is spacing between precipitates.

Table 1. The contribution of precipitate resistivity to the total resistivity varying with separation spacing between precipitates [8].

Separation between precipitations	Contribution to total resistivity
10 nm	15-25 %
10-100 nm	10-15 %
Up to 1000 nm	Below 5 %

In theoretical assumption, it is considered that scattering from precipitates, metastable precipitates, and solute clusters have similar behaviour but experimental observations show that precipitate resistivity must be taken into account especially for those precipitates which strengthen the alloys. Consequently, it was found the effect on electrical resistivity due to different ageing temperatures of aluminium alloy and came to know that at higher temperatures resistivity due to precipitates can be ignored and lower temperatures of precipitates resistivity must be taken into account. According to these results, Matthiessen's rule can be modified which includes the term precipitate resistivity. By using this rule, the range of precipitate can be identified (where it is effective and where it is not).

Aluminium alloy with different heat treatment conditions shows that resistivity decreases uniformly within the temperature range liquid helium to ice point[12]. Resistivity measurements of these alloys can be used to correlate with their other properties e.g. electrical conductivity, precipitation hardening, etc. The relation between electrical resistivity and electrical conductivity (λ_e) is given by the Lorentz ratio.

$$L = \rho \frac{\lambda_e}{T} \tag{4}$$

where L is the Lorentz number.

Uncertainty in the measurements of aluminium is 0.4% which arises due to systematic error as well as two voltage measurements rather imprecision in the size of sample and voltage measurements because these errors are much less than systematic error. For these measurements, the electrical resistivity dip probe method can be used and for numerical calculations, a simple formula can be useful.

Computational and Experimental Research
in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

$$\rho = \frac{E}{I} \times \frac{A}{L} = R_S \frac{A}{L} \tag{5}$$

Graphical analysis of these measurements can be useful to show their behaviour according to change in temperature as well as heat tempering.

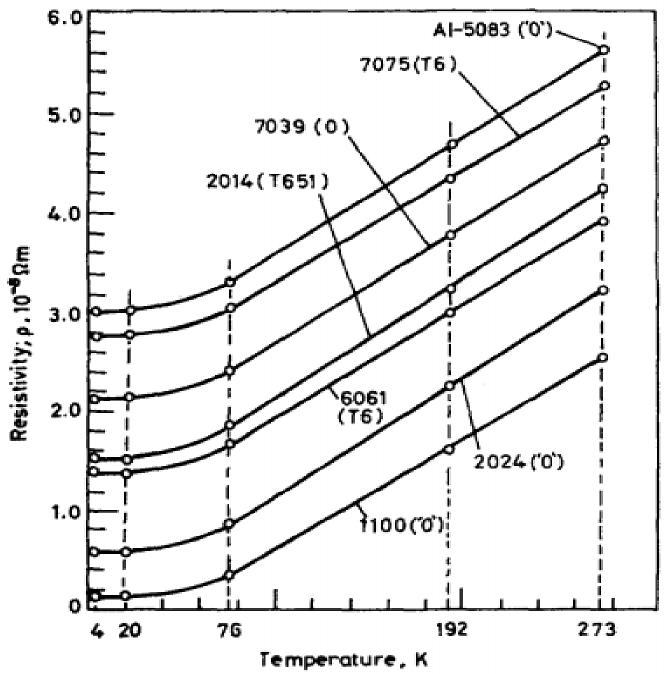

Figure 4. Electrical resistivity of aluminium alloys [12].

The figure shows that alloys behave similarly with variation in temperature regardless of composition and heat treatment. So curve plots from room temperature measurements can be extrapolated to check the low-temperature behaviour of these or new aluminium alloys. Except Al 5083 and Al 2024, which have larger and smaller resistivities respectively corresponding to larger and smaller content of impurity, there is also a rise in resistivity of alloy and alloy scales with a rise in impurity content [12]. Heat treatment may change the phase structure of the specimen and can be done in four different ways (‘o’, T4, T6, and T86). The ‘o’ is the condition of heated alloy and cools slowly to form large precipitates that will separate; thus scattering is reduced. The ‘T4’ condition is naturally aged heated solid solutions while ‘T6’ is aged artificially so fine-scale precipitates will form to lower the resistivity. The final one is ‘T86’in which solution anneal and cold working is done during artificial ageing and resistivity increase due to imperfections (due to cold working).

3. Resistivity of nanoparticles of Al alloy

The introduction of nanoparticles in the matrix influences the electrical, magnetical, optical as well as mechanical properties. Aluminium alloy and nanoparticles introduced into them have specific characteristics e.g. high electrical resistivity, heat resistance, yield strength, plasticity, hardness, etc[20]. It has been found that if the grain size of the doped nanoparticles sample is much smaller

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

than the original one than electrical resistivity will increase because there would greater number of grains consequently there would be large grain boundary to hinder the charge carrier and reverse phenomenon will occur when grain size of sample embedded with nanoparticles is significantly larger than the original sample. Smaller grain size also reduces the surface contact area between grains due to which motion of charge carriers reduces and resistivity will increase[21]. But it was found in [13] that grain size of 6061 alloy increases from (155 μm to 240 μm for wt. 0.5 %) when nanoparticles of alumina are introduced. So resistivity will decrease according to [14]. But increment in the consecration of nanoparticles causes a decrease in the grain size consequently resistivity increases. Change in the cooling rate of the alloy will change the size of grains.

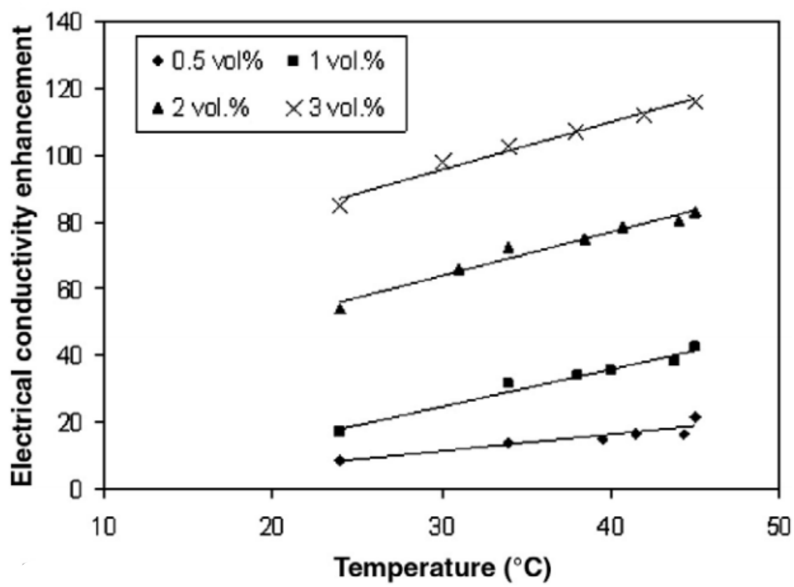

Figure 5. Relations of resistivity with concentration and temperature of nanoparticles [15]

The figure shows that when concentration increases the inverse of electrical resistivity increases and similar behaviour has shown by temperature increment. The decrease in resistivity with increasing temperature symbolises the semiconductor behaviour. When temperature increases the drift mobility of charge carriers increases due to thermal effects consequently resistivity will increase. Basically in nanomaterials, there is little probability of overlapping the wave function of electrons of ions located at an adjacent site. But probability will increase when the temperature increases because ions vibrate more violently and transfer their electrons with each other as the resulting resistivity will decrease.

4. Conclusion

The present review revealed that the resistivity of Al alloy is at low temperatures and is dependent upon temperature. At very low temperature (below 20 K) it is proportional to T^5 and at low temperature (above 20 K and below 12th part of Debye temperature) resistivity is proportional to T^3 and resistivity has linear relation at high temperature (this is experimental verification of Bloch-Gruneisen theoretical calculations). From the behaviour of Al alloy, we demonstrate that residual

Computational and Experimental Research in Materials and Renewable Energy (CERiMRE)
Volume 5, Issue 2, page 133-141
eISSN : 2747-173X

Submitted : August 19, 2022
Accepted : November 10, 2022
Online : November 11, 2022
DOI : 10.19184/cerimre.v5i2.33637

resistivity is nearly constant at any temperature. We prove that if any metal is in the pure form its resistivity becomes zero at absolute zero temperature and if the metal is impure resistivity becomes constant at specific temperatures (called residual resistivity). Furthermore it has also been scientifically proven that resistivity of nanoparticles of aluminium increases with the increase in temperature

References

[1] C. H. Yin, Z. H. Gan, S. H. Wang, D. L. Liu and L. M. Qiu, "The measurement of RRR and resistance for aluminum alloy based on a cryocooler," Cryocoolers, vol. 19, pp. 605-612, 2016.

[2] Clark, A.F, Childs, G.E, Wallace, G.H, “Electrical resistivity of some engineering alloys at low temperatures,” Cryogenics, vol. 456, pp. 295-305, 1970.

[3] Qiu, L.M, Zhang, K.H, Dong, W.Q, et al, “Study of mass flow distribution between stages in a two stage pulse tube cryocooler capable of 1.1 W at 4.2 K,” International Journal of Refrigeration, vol. 35(8), pp. 2332-2338, 2012.

[4] R. Krsnik, E. Babic and C. Rizzuto, “Phonon resistivity in concentrated aluminum alloys,” Solid State Communications, Vol. 12, pp.891—895, 1973.

[5] Jack Bass “Deviations from Matthiessen's Rule,” Advances in Physics, Vol. 21,pp. 431-604, 1972.

[6] T. Fujita, T. Ohtsuka, “Transport properties of cold-worked aluminum at low temperatures,” Journal of Low Temperature Physics, vol.29, pp.333–344, 1977.

[7] A. Fert, “Transport in magnetic alloys: scattering asymmetries (anisotropic scattering, skew scattering, side-jump)” Physica B+C, Volumes 86–88, Part 1, pp. 491-500, 1977.

[8] Raeisinia, Babak & Poole, Warren & Lloyd, D., “Examination of precipitation in the aluminum alloy AA6111 using electrical resistivity measurements,” Materials Science and Engineering A, vol. 420, pp. 245–249, 2006.

[9] C. Panseri, T. Federighi, “Interpretation of quench-sensitivity in Al-Zn-Mg-Cu Alloys,”Metallurgical Transactions, vol. 94, pp. 99-107,1973.

[10] P.L. Rossiter, P. Wells, “The dependence of electrical resistivity on short-range order,” J. Phys., vol. 4, pp. 354–363,1966.

[11] A.J. Hillel, J.T. Edwards, P. Wilkes, “Examination of precipitation in the aluminum alloy AA6111 using electrical resistivity measurements,” Phil. Mag, Vol. 32, pp. 189–209,1975.

[12] A. F. Clark, G. E. Childs, and G. H. Wallace, “Electrical resistivity of some engineering alloys at low temperatures,” Cryogenics, vol. 8, pp.182-183,1970.

[13] J. J. Dick and D. L. Styris, "Electrical resistivity of silver foils under uniaxial shock-wave compression," J. Appl. Phys, vol. 4, pp. 1602-1617, 1975.

[14] Vladimir Valikhov, Nikolay Kahidz, Anton Khrustalyov, Ilya Zhukov and Alexander Vorozhtsov, “Investigation of structure, mechanical properties and crystallization of aluminum alloys containing aluminum oxide nanoparticles,” MATEC Web of Conferences, vol. 9, pp. 65-76, 2018.

[15] Yadunath Singh, “ELECTRICAL RESISTIVITY MEASUREMENTS: A REVIEW,” International Journal of Modern Physics: Conference Series Vol. 22 (2013) 745–756