INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Comparative Studies of NiMgCuZn composite ferrites with Equimolar (NiCuZn+MgCuZn) Nanocomposite ferrite useful for Microinductors Applications

N.Varalaxmi1, K.V.Sivakumar2
1Department of Physics, Kakatiya University,Warangal, India
2Ceramic Composite Materials Laboratory, Department of Physics, Sri Krishnadevaraya University, S.V. Puram, Anantapur - 515 003, India

Abstract

In this paper, we report a comparative study on structural, magnetic, electric properties and stress sensitivity of the Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4 with equimolar nano composite ferrite 0.5[(Ni0.15Cu0.15Zn0.4Fe2O4)+(Mg0.125Cu0.125Zn0.5Fe2O4)] prepared by conventional double sintering technique, with a view to develop a ferrite composition for its use as core material for microinductor applications. The structural properties were estimated from X-ray diffraction patterns which confirms the formation of single phase cubic spinel structure and the grain size was estimated using SEM micrographs. Initial permeability measurements of samples were carried out in the temperature range of 30-400 °C at 10°C temperature intervals, it was noticed that the initial permeability of Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4 sample is drastically reducing when compared to equimolar composite ferrite. The effect of the external applied stress on the open magnetic circuit type coil with these ferrites was studied by applying uniaxial compressive stress parallel to magnetizing direction and the change in the inductance was measured. The variation of ratio of inductance (ΔL/L)% with external applied compressive stress was examined.

Keywords: Microinductor applications, Magnetic properties, X-Ray diffraction, SEM

Patterns, Ferrites, Stress Sensitivity..

Introduction

A considerable amount of research in recent years has focused on NiCuZn and MgCuZn ferrites, because of their excellent properties which possesses innumerable electronic applications, communication industries also having much importance in microinductors, both have similar electromagnetic properties which are suitable for core materials in microinductors, with the advantage that they are economic [1] and easy to synthesize. Especially they are potential candidate materials for multilayer chip inductors with high performance and low cost. Microminiaturization of electronic circuits especially in the fields of mobile communication and information technology demands electronic components with very small size [2]. Multilayer chip inductor (MLCI) as key component of electronic devices confronts new challenges [3]. Better magnetic properties, especially required high initial permeability for reducing the number of layers of multilayer chip inductors (MLCI) minimizing the capacity between the layers and realizing the miniaturisation [4]. So far, NiCuZn and MgCuZn ferrites have been used extensively for the production of the MLCI [5] due to their better magnetic properties and low temperature sintering [6-7]. However, they suffer from stress sensitivity [8-10]. It is believed that increase of initial permeability can be obtained by decreasing magnetostriction constant [4,11]. As the magnetostriction constant of MgCuZn ferrite is lower than that of NiCuZn ferrite [5], it is also expected that the multilayer chip inductor (MLCIs) using MgCuZn ferrites [4] would show higher magnetic properties [9-10,12] making further miniaturization possible than that of NiCuZn ferrites, compared to that of NiCuZn ferrites one can realize at low cost MLCIs with MgCuZn ferrites. The growing interest during the past decade is essentially due to the possibility of a reduction in manufacturing cost on account of energy savings.

We aimed to produce low-cost ferrite materials according to the desired application with easy and synthesis technique. In search of the suitable ferrite materials for microinductor applications, assuming that the ferrite composites would yield enhanced magnetic properties. Initially, composite ferrites were prepared in this laboratory by choosing NiCuZn and MgCuZn ferrite compositions. As reported earlier these composites [10] showed high initial permeability, fairly high resistivity and stress insensitivity. As the part of continuation, the two compounds can be successfully incorporated into a single composite, it is expected that the composites might have interesting electrical as well
as magnetic properties, it’s very interesting to study the electromagnetic properties of composition dependence by considering the stoichiometric formula of each composition \((\text{Ni}_{0.35}\text{Cu}_{0.05}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4 \text{ and Mg}_{0.35}\text{Cu}_{0.35}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4)\) and the resulting sample was \((\text{Ni}_{0.175}\text{Mg}_{0.125}\text{Cu}_{0.125}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4)\). So, in view of this, an attempt has been made to develop ferrite material suitable for MLCI and studies on magnetic, electrical and stress sensitivity has been investigated and the results are discussed and compared with the equimolar composite.

**Experimental**

In previous research we studied the magnetic, electrical and stress sensitivity properties of composite ferrite \((X)\) \(\text{Ni}_{0.35}\text{Cu}_{0.05}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4 + (1-X)\) \(\text{Mg}_{0.35}\text{Cu}_{0.35}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4\) in which \(X\) varies from 0.0 to 1.0 [10] which predicts that both the end compositions i.e., pure ferrite’s have almost equal initial permeability values also undergoes stress insensitivity and the equimolar composite ferrites i.e., \((0.5)\) \(\text{Ni}_{0.175}\text{Mg}_{0.125}\text{Cu}_{0.125}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4\) exhibits high initial permeability value of \(\mu_i = 9619\). So, keeping in point of view, we thought of investigating the properties of \(\text{Ni}_{0.175}\text{Mg}_{0.125}\text{Cu}_{0.125}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4\) (generic formula has taken from the end compositions ferrites i.e., \(\text{Ni}_{0.35}\text{Cu}_{0.05}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4\) and \(\text{Mg}_{0.35}\text{Cu}_{0.35}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4\)) in the present study an attempt is made on these ferrites composites, to investigate their electrical properties as well as thermoelectric effect studies were carried out with an intention of developing a ferrite composition suitable for multilayer chip inductors and the results are reported in this paper.

**Preparation of ferrites:**

The composite ferrite was prepared by choosing the stoichiometric of each composition i.e., \((\text{Ni}_{0.35}\text{Cu}_{0.05}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4 \text{ and Mg}_{0.35}\text{Cu}_{0.35}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4)\) and the resulting sample with the generic formula \(\text{Ni}_{0.175}\text{Mg}_{0.125}\text{Cu}_{0.125}\text{Zn}_{0.35}\text{Fe}_2\text{O}_4\) were prepared employing double conventional sintering method using analytical grade \(\text{NiO, MgO, CuO, ZnO and Fe}_2\text{O}_3\). These oxides were weighed and intimately mixed in stoichiometric proportions. These constituents were then milled in a planetary ball mill (RETSCH PM-200) in acetone medium using polyethylene jars with iron balls (\(\varphi = 5\)mm) for 24 hrs and then dried in an oven. The ground powders were presintered at 800 °C for 4hrs in the form of cakes in alumina crucibles. After presintering, these cakes were crushed and ball milled once again for 8 hrs to obtain fine particle size and finally, these powders were sieved to get uniform particle size.

The presintered green powders were mixed with 2% polyvinyl alcohol as a binder and were compacted in the form of torroids of \(12 \times 10^{-3}\) m outer diameter (O.D) ., \(8 \times 10^{-3}\) m inner diameter (I.D) and \(4 \times 10^{-3}\) m height (h), also in the form of pellets of \(10 \times 10^{-3}\) m diameter and \(2 \times 10^{-3}\) m thickness and cylinders of diameter \(10 \times 10^{-3}\) m and length nearly \(20 \times 10^{-3}\) m long using an isostatic press at 150 MPa. These compacted bodies were finally sintered at 1050 °C for 2 hrs in a programmable furnace and were cooled to room temperature at the rate of 80 °C/hr. Sufficient care was taken to avoid the zinc loss during the sintering process by placing these compacted pellets, cylinders and torroids in a closed alumina crucible with excess of \(\text{ZnO}\) rich atmospheric powder. All the samples were structurally characterized using Philips high resolution x-ray diffraction system (Model PW-1710 X-ray diffractometer) with monochromatic CuK\(_\alpha\) radiation at room temperature.

Microstructures of sintered samples were recorded with the help of using SEM (Philips XL30ESEM) Scanning electron microscope instrument Thermally etched samples were taken for making the SEM specimens. The samples were mounted on brass studs with double sided adhesive tape and coated with Au-Pd alloy of 120-150 Å thickness of argon ambient atmosphere of 8-10 Pascal. Then the sample is scanned for various surfaces and the best photographs were recorded.

**Experimental details:**

**Initial permeability**

The initial permeability, \(\mu_i\) of these ferrite torroids were evaluated using the standard formulae from the inductance measurements carried out at 1 KHz using computer controlled impedance analyzer (Hioki Model 3532-50 LCR HiTester, Japan). These measurements were carried out in the temperature range of 30 to 400 °C using the formula [9].

\[
L = 0.0046N^2 * \mu_i * h * \log_{10} \left( \frac{D_1}{D_2} \right) \quad (1)
\]

Where \(D_1\) and \(D_2\) are the inner and outer diameter of the torroid in inches, \(L\) is the inductance in microhenrys, \(h\) is the height of the torroid in inches and \(\mu_i\) is the initial permeability of the core and \(N\) is the number of turns.

**Stress sensitivity studies**

In order to study the effect of external stress, uniaxial compressive stress parallel to the magnetizing direction was applied to the cylindrical shaped ferrite cores using uniaxial press system. The stress magnitudes were varied from 0 to 10 MPa. The change in inductance was measured using the above mentioned LCR HiTester.
by employing 100-120 turns coil wound on each cylinder.

**DC electrical conductivity**

DC electrical conductivity measurements were carried out with laboratory designed cell having guarded ring facility in addition to the two probe method [13]. It consists of an electrically heated furnace, a digital DC voltmeter and a transistorized power supply unit as a source of DC voltage. Silver paste was applied to both the surfaces of the pellet to obtain good ohmic contacts. The pellet was mounted in a sample holder consisting of two silver rods in which the sample can be sandwiched with the help of screws. The cell was placed in a tube furnace. A calibrated cromel-alumel thermocouple was used to measure the temperature of the tube furnace. The measurements of conductivity were carried out by measuring the current at a constant voltage of 5 volts from a regulated power supply, room temperature resistivity was determined by the relation.

\[ \rho = \left( \frac{\pi r^2}{t} \right) \left( \frac{V}{I} \right) \]  

...... (2)

and the electrical conductivity (\(\sigma\)) of MgCuZn ferrites under investigation has been computed using the formula.

\[ \rho = \left( \frac{It}{VA} \right) \]  

...... (3)

Where, \(t\) is the thickness of the sample in cm, \(r\) is the radius of the disc in cm, \(I\) is the current passing through the specimen in amperes, \(A\) denotes the area of a cross section of the sample in cm\(^2\) and \(V\) is the voltage applied of the specimen in volts.

**AC electrical conductivity**

The AC electrical conductivity (\(\sigma_{AC}\)) of these ferrites was evaluated using the following standard relation.

\[ \sigma_{ac} (\omega) = \frac{Z'}{(Z^2 + Z''^2)} \cdot X \cdot \frac{t}{A} \]  

...... (4)

Where"t" is the thickness of the pellet and \(A\) is the area of a cross-section of pellet.

Using Eq. (4), the AC conductivity, \(\sigma_{AC}\) of these ferrites was evaluated from the real (\(Z'\)) and imaginary parts (\(Z''\)) from directly obtained impedance values at 1 kHz employing a computer controlled low frequency impedance analyzer (Hioki 3532-50 LCR Hi-Tester) in the temperature range 30 to 490 °C. The measurements of \(Z'\) and \(Z''\) were also made at different frequencies in the range 100 Hz to 1 MHz at room temperature and \(\sigma_{AC}\) was evaluated.

**Thermo-electric power**

Thermo-electric power measurements were made in the temperature region 30 to 360°C by the differential method similar to that of Reddy et.al., [14] with a few modifications. It contains a main furnace assembly, DC micro-voltmeter, sample holder, and digital micro-voltmeter. The sample holder consists of a small independent heater in intimate contact with the top electrode that facilitates the setting of the temperature of the upper electrode at any desired value. The mechanical assembly of thermo-electric power set-up has the provision to mount the pellet between the top and bottom electrodes with a spring loading arrangement. Before loading the sample into the sample holder, the surfaces of pellet were coated with silver paste for good ohmic contact. The entire mechanical assembly was placed inside a tube furnace for the measurement of thermo-electric power. The details of the furnace and the temperature controller assembly were described elsewhere [15]. Employing the arrangement a temperature difference of 10 K was produced across the pellet with the help of a micro furnace fitted to the sample holder assembly. The sample was then heated, and thermo-emf was recorded at different temperatures. In the measurement of the thermo-emf, the micro-voltmeter gives a positive deflection by connecting its positive terminal to the hot end of the sample. This happens in case of an N-type charge carrier. This situation reverses when the charge carriers are of P-type. Thermo-electric power was determined by using the relation.

\[ \alpha = \left( \frac{\Delta V}{\Delta T} \right) \]  

...... (5)

Following convention adopted by Lal et.al., [16].

The sample was maintained at a given temperature for about 15 minutes for attaining thermal equilibrium. The thermo-emf measurements were made after the attainment of thermal equilibrium. The temperature was measured using calibrated chromel-alumel thermocouple.

**Results and Discussion**

**Structural and Microstructures of the NiMgCuZn ferrite:**

Fig.1 (a), shows the typical XRD pattern of Ni\(_{0.175}\)Mg\(_{0.125}\)Cu\(_{0.15}\)Zn\(_{0.55}\)Fe\(_{2}\)O\(_4\)
sintered at 1050 °C. The formation of all the peaks i.e., (220), (311) (222) (400) (442) (511) and (440) is the evidence that the sintered samples contain only spinel cubic structure, no second phase was detected. Fig.1 (b) shows equimolar composite sintered at 1250 °C confirms the formation of single phase cubic structure, which also shows that the (222),(400) (442) (511) and (440) peaks which belong to octahedral and tetrahedral sites are maximum suppressed in the equimolar composition of ferrite composite i.e 0.5((Ni0.35Cu0.05Zn0.6Fe2O4)+ (Mg0.25Cu0.25Zn0.5 Fe2O4)) when compared to Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4, also it can be noticed that the intensity of (311) peak is maximum in equimolar composition when compared.

The interplanar distance d (Å) were calculated using Bragg's law. The lattice parameter “a” was calculated using the relation [17].

\[
\frac{1}{d^2} = \left(\frac{h^2 + k^2 + l^2}{a^2}\right) \quad ...... (6)
\]

Where “a” is the lattice constant, (hkl) are the Miller indices and “d” is the interplanar distance. The lattice parameters have been determined using the method of least squares to an accuracy of ± 0.007Å.

The calculated lattice parameter identified the samples to be cubic spinel. The crystalline sizes for each composition are calculated from XRD line width of the (311) peak using Scherrer formula [18]. The values of the particle size, lattice constant (a), measured density (ρm) and the X-ray density (ρx) as reduced from the X-ray data are given in Table.2. The measured density (ρm) is determined using the formula.

\[
\rho_m = \frac{m}{r^2h} \quad ...... (7)
\]

Where “m” is the mass, “r” the radius and “h” is the height of the samples.

The X-ray density of the prepared samples was calculated from the relation.

\[
\rho_x = \frac{8M}{Na^3} \quad ...... (8)
\]

where M is the molecular weight of the samples, N is the Avogadro’s number and “a” is the lattice constant.

It can be noticed from Table.2 which shows the variation of the lattice parameters of the both the end products, equimolar composite and Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4 the lattice parameter exhibit a decrease in Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4 when compared to equimolar composition, it can be explained on the basis of the relative ionic radius of ions [19-20]. The ionic radius of Mg²⁺ = 0.65 Å, which has smaller radius when compared to Ni²⁺ = 0.72 Å, Cu²⁺ = 0.72 Å, Zn²⁺ = 0.74 Å and Fe²⁺ = 0.64 Å which are larger in radius may cause a decrease of lattice constant may be logically attributed due to the difference in the ionic radius, which results in the reduction of the unit cell.

The variations of X-ray density and measured density are given in Table.2. It can also be observed from Table.2 the mass density is slightly higher than the X-ray density of the sintered samples. This may be due to the existence of pores formed during the sintering process, also one can notice that mass density (ρm) of Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4 is greater than the equimolar composite.

Percentage porosity (P) of the samples was calculated from ρx and ρm values using the expression [21].

\[
P = \left(1 - \frac{\rho_m}{\rho_x}\right) \quad ...... (9)
\]

Grain size is the more important parameter affecting the magnetic properties of ferrites. It is well known that ferrites with high density and larger average grain size possess high initial permeability.

(b) Scanning electron micrographic (SEM) studies

The scanning electron micrograph for equimolar composite and Ni0.175Mg0.125Cu0.15Zn0.55Fe2O4 are shown in Fig.2, which shows a systematic grain structure having clear grain boundaries indicating a microstructure, having high density and having large grain size. But it is interesting to note that the morphology of grains is different in both the compositions. However, the initial permeability’s values obtained are fairly high. This may be attributed to the initial permeability being a result of the easy reversal of domain wall displacement in the direction of the applied magnetic field, the greater the number of domain walls, the higher the initial permeability.

Magnetic properties:

Initial permeability is known to be one of the most sensitive magnetic properties of ferrites, and also it is a very sensitive parameter that depends on various factors like external stress, grain size, temperature, and method of preparation, etc., an
important requirement for MLCI fabrication is the low sintering temperature of the ferrite materials. For MLCI applications, the temperature dependence of initial permeability is important. The initial permeability (µi) of low-temperature sintered Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.125}$Zn$_{0.55}$Fe$_2$O$_4$ along with equimolar composite and its ends products at room temperature are shown in Table.3.

The variation of initial permeability (µi) with temperature Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.125}$Zn$_{0.55}$Fe$_2$O$_4$ is shown in Fig.3, the initial permeability increases with an increase in temperature; these phenomena were considered to be due to a faster decrease in the anisotropy field rather than a decrease in a saturation field. The variation of initial permeability with temperature shows the presence of two slopes before reaching the Curie temperature [23]. The variation of initial permeability with temperature shows the presence of two slopes before reaching the Curie temperature (Tc). The variation of initial permeability with temperature shows the presence of two slopes before reaching the Curie temperature (Tc). The variation of initial permeability with temperature shows the presence of two slopes before reaching the Curie temperature (Tc). The variation of initial permeability with temperature shows the presence of two slopes before reaching the Curie temperature (Tc).

Stress sensitivity studies:

Fig.4 shows the graphically represented data of the ratio of inductance change (ΔL/L) % as a function of applied compressive stress for equimolar composite and Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.125}$Zn$_{0.55}$Fe$_2$O$_4$. An examination of the Fig.4 indicates that in Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.125}$Zn$_{0.55}$Fe$_2$O$_4$ (ΔL/L)% increases up to a certain applied stress and thereafter, it remains constant and found to be less stress sensitive. In all the samples studied in this series the (ΔL/L)% values are positive in the entire region of the applied stress applied. Exactly, similar behaviour was noticed by [9-10, 25].

Stress sensitivity studies:

The DC electrical resistivity is an important property of low temperature sintered for MLCS. A C conductivity also shows a similar trend. The room temperature values of DC resistivity (ρDC). DC conductivity (σDC). AC resistivity (ρAC), AC conductivity (σAC) along with seebeck coefficient values for all the compositions are presented in the Table.3.

Hall effect and Thermo-electric properties are widely used in the interpretation of the conduction mechanism in semiconductors. In case of low mobility materials such as ferrites, it’s sometimes difficult to measure the Hall effect in such cases the thermo-electric power measurement is the only alternative. The sign of the thermo emf gives the vital information about the type of conduction in semiconductors, whether it’s P or N type. Another important significance of thermo emf is that it enables one to calculate the values of Fermi-energy that help in the determination of the various regions, viz., Impurity conduction, impurity exhaustion and intrinsic conduction regions of the semiconductor. As can be observed from the values of Table.3. All the compositions exhibit positive Seebeck Coefficient. Showing that they behave as P- type materials.

Stress sensitivity studies:

Fig.4 shows the graphically represented data of the ratio of inductance change (ΔL/L) % as a function of applied compressive stress for equimolar composite and Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.125}$Zn$_{0.55}$Fe$_2$O$_4$. An examination of the Fig.4 indicates that in Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.125}$Zn$_{0.55}$Fe$_2$O$_4$ (ΔL/L)% increases up to a certain applied stress and thereafter, it remains constant and found to be less stress sensitive. In all the samples studied in this series the (ΔL/L)% values are positive in the entire region of the applied stress applied. Exactly, similar behaviour was noticed by [9-10, 25].

These variations of permeability with applied compressive stress can be attributed to the magnetostrictive contributions of varied amounts of nickel (λs = -26 x 10$^{-6}$), and iron (λs = -19.5 x 10$^{-6}$) present in these samples [26]. For small compressive stresses, the stress raises initial permeability with negative magnetostriction and for large tensile stresses the permeability decreases [27].

Conclusions

The attempt is made in order to achieve high initial permeability, to develop a soft magnetic ferrite useful for microinductor applications, and is compared with equimolar composite ferrite. Thus low temperature sintered Ni$_{0.175}$Mg$_{0.125}$Cu$_{0.15}$Zn$_{0.55}$Fe$_2$O$_4$ samples also possess good electromagnetic properties, as well as fine-grained microstructures, making them suitable materials for MLCIs having high performance and low cost.

Acknowledgments

This work was financially supported by Defence Research and Development Organization (DRDO), under the grants ERIP/ER/0103301/M/01, New Delhi, India. The author is thankful to the authorities of Sri Krishnadevaraya University, Anantapur for providing the facilities.

Conflict of Interests Section

The authors declare that there is no conflict of interests regarding the publication of this article

References


Comparison of the Results

<table>
<thead>
<tr>
<th>S.No</th>
<th>Properties</th>
<th>Compositions</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\text{Ni}<em>{0.175}\text{Mg}</em>{0.125}\text{Cu}<em>{0.15}\text{Zn}</em>{0.55}\text{Fe}_2\text{O}_4$</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Average grain size 't'($\mu$m)</td>
<td>6.51</td>
<td>4.11</td>
</tr>
<tr>
<td>2.</td>
<td>Porosity</td>
<td>0.082</td>
<td>0.072</td>
</tr>
<tr>
<td>3.</td>
<td>Lattice constant A(Å)</td>
<td>8.408</td>
<td>8.414</td>
</tr>
<tr>
<td>4.</td>
<td>X-ray density ($\rho_v$) gm/cc</td>
<td>5.013</td>
<td>5.062</td>
</tr>
<tr>
<td>5.</td>
<td>Measured density($\rho_m$) gm/cc</td>
<td>5.426</td>
<td>4.978</td>
</tr>
<tr>
<td>6.</td>
<td>Initial Permeability $(\mu_i)$</td>
<td>2580</td>
<td>9619</td>
</tr>
<tr>
<td>7.</td>
<td>Curie Temperature $T_c$(°C)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>8.</td>
<td>$\rho_{DC}$ at RT Ω Cm</td>
<td>$3.694 \times 10^4$</td>
<td>$3.316 \times 10^2$</td>
</tr>
<tr>
<td>9.</td>
<td>$\rho_{AC}$ at RT Ω Cm</td>
<td>$2.303 \times 10^7$</td>
<td>$1.676 \times 10^7$</td>
</tr>
<tr>
<td>10.</td>
<td>$\sigma_{DC}$ at RT Ω$^{-1}$ Cm$^{-1}$</td>
<td>$2.707 \times 10^7$</td>
<td>$3.016 \times 10^{-10}$</td>
</tr>
<tr>
<td>11.</td>
<td>$\sigma_{AC}$ at RT Ω$^{-1}$ Cm$^{-1}$</td>
<td>$4.342 \times 10^{-8}$</td>
<td>$5.967 \times 10^{-10}$</td>
</tr>
<tr>
<td>12.</td>
<td>Seebeck Coefficient $\alpha$ µV/K</td>
<td>+1681</td>
<td>+2180</td>
</tr>
<tr>
<td>13.</td>
<td>Stress sensitivity Studies (ratio of inductance change (ΔL/L)) %</td>
<td>Positive and low stress sensitivity</td>
<td>Positive and low stress sensitivity</td>
</tr>
</tbody>
</table>