CHAPTER 1

INTRODUCTION

1.1 GENERAL

World energy requirement has been increasing continually and is projected for a strong increase by 50 percent from 2005 to 2030 (International Energy Outlook 2009). To maintain economic prosperity and quality of life, a sustainable energy system is required to meet the conflicting demands for increased supply and energy security, whilst maintaining cost competitiveness and reducing climate change.

Clean electric power without engines were a dream of the engineers and environmentalists until solar panels and wind farms which are familiar sources of alternative energy came into existence. Due to their poor stability of energy at all times there was a problem of considering them to be effective sources of electric energy.

In order to solve these problems, some clean sources of energy, such as hydrogen, which don't produce pollutants or greenhouse gases need to be developed. Fuel cell which uses hydrogen is seen as possible key solution for the 21st century (Hydrogen Energy and Fuel Cells 2003). Fuel cells offer several advantages compared with the conventional methods.

As an energy converter of hydrogen, fuel cells harness the chemical energy of hydrogen to generate electricity which is considered as more efficient, quiet, and pollution-free power sources in comparison with

Extracting electricity from a device called as “solid electrolyte fuel cell” was demonstrated by the scientists and since then there has been an intense research and development effort on alternative energy technology known as fuel cells. Now, as energy issues are at the forefront of current events, fuel cell technology is ripening and on the verge of being ready for large scale commercial implementation.

1.2 FUEL CELL

Fuel cells are electrochemical devices that convert chemical energy in fuels directly into electrical energy by a process involving an essentially invariant electrode electrolyte system. A fuel cell is electrochemically similar to a battery; however, a fuel cell uses externally supplied fuels, while a battery consumes internal fuels to generate electricity. A fuel cell can produce electricity continuously as long as the fuel is supplied; by contrast a battery needs to be recharged once the internal fuel is used up.

A fuel cell combines hydrogen and oxygen to produce electricity. The basic principle of the fuel cell is illustrated in Figure 1.1. The core of each fuel cell consists of an electrolyte and two electrodes. At the negative anode, a fuel such as hydrogen is being oxidized, while at the positive cathode, oxygen is reduced. Ions are transported through the electrolyte from one side to the other (Haile 2003, Stambouli & Traversa 2002). The type of electrolyte determines the temperature window of operation. This window of operation in its turn determines the catalysts that can be used, and the purity of the fuel to be used.
The theoretical open circuit voltage of a hydrogen-oxygen fuel cell is 1.23 V at 298 K, in practice it is around 1 V at open circuit. Under load conditions, the cell voltage is between 0.5 and 0.8 V.

(Source: http://www.fuelcell.no/principle_mainpage_eng.htm)

**Figure 1.1 Operating principle of the fuel cell**

Fuel cells are not limited by thermodynamic limitations of heat engines such as the Carnot efficiency; therefore, they have much higher efficiency than current thermo-mechanical methods.

There are many different types of fuel cell technologies that are currently being developed. Out of the types only the Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) (EG & G Technical Services I 2004) are being considered for bulk power generation. The Proton Exchange Membrane Fuel Cell (PEMFC) is being considered for small-scale residential generation. Fuel cells are...
classified after the electrolyte they use as ion conducting medium, excluding the case of Direct Methanol Fuel Cells (DMFC), which is identified by the fuel that is being used.

This research mainly focuses on SOFC, hence Solid Oxide Fuel Cell alone is being discussed in this chapter and the other details and types are discussed in the next chapter.

1.3 SOLID OXIDE FUEL CELL

Solid oxide fuel cells can be considered as the “most efficient” devices yet invented for conversion of chemical fuels directly into electrical power. It is characterized by the use of a solid oxide material as the electrolyte, which acts as a conductor of oxygen ions. Figure 1.2 shows the scheme of operation of SOFC. There are three basic components of SOFC: a porous anode, an electrolyte, and a porous cathode (Haile 2003, Stambouli & Traversa 2002). The operation of the solid oxide fuel cell is straightforward.

Typically, oxygen atoms are reduced on the porous cathode surface by electrons. The oxygen ions diffuse through the electrolyte to the fuel rich and porous anode, where they react with the fuel (hydrogen) and give off electrons to an external circuit. Thus, the final products of SOFC are electricity, heat and water.

SOFC normally operates at very high temperatures, typically between 800 and 1000°C. Because of these high temperatures, light hydrocarbon fuels, such as methane and alcohol, can be used as fuel as they can be internally reformed within the anode. The SOFC doesn’t suffer from anode poisoning and can also operate on fuels such as hydrocarbons or natural
The other types of fuels that can be used for SOFC are discussed in the next chapter.

![Scheme of the operating principle of a solid oxide fuel cell](https://en.wikipedia.org/wiki/Fuel_cell)

**Figure 1.2 Scheme of the operating principle of a solid oxide fuel cell**

SOFCs are classified as intermediate and high temperature solid oxide fuel cells. Intermediate temperature SOFCs (IT-SOFC) operate in the range of 500-800°C, using ceria-doped rare earth electrolytes. High temperature SOFCs (HT-SOFC) use yttrium stabilized zirconia (YSZ) and operate in the range of 800-1000°C. Low Temperature SOFCs (LT-SOFC) operate in the ranges below 500°C. Solid oxide fuel cells operate at temperatures where certain oxide electrolytes become conducting. There are two different types of the solid oxide fuel cell, tubular and planar. Each type has its own advantages and disadvantages.

The efficiency of a solid oxide system is just under 50% but when used as a CHP system, the efficiency is around 80%. SOFCs can also be
fueled by externally reforming heavier hydrocarbons, such as gasoline, diesel, or biofuels. Such reformates are mixtures of hydrogen, carbon monoxide, carbon dioxide, steam and methane, formed by reacting the hydrocarbon fuels with air or steam in a device upstream of the SOFC anode (Badwal & Foger 1996, Kharton et al. 2004, Zhu & Deevi 2003). SOFC power systems can increase efficiency by using the heat given off by the exothermic electrochemical oxidation within the fuel cell for endothermic steam reforming process. Internal reforming also leads to a large decrease in the balance of plant costs in designing a full system. This specific type of fuel cell has the longest operational life. With a span of 69,000 hours, it is the fuel cell that has the greatest life expectancy.

Solid oxide fuel cells have a wide variety of applications from use as auxiliary power units in vehicles to use as stationary power generation with outputs from 100 W to 2 MW. Theoretical efficiency of a SOFC device can exceed 60 percent. The high operating temperature makes SOFCs suitable candidates for application with heat engine energy recovery devices or combined heat and power, which further increases overall fuel efficiency. These capabilities have made SOFC an attractive emerging technology for stationary power generation system (Kordesch & Simader 1996, Carrette et al. 2001, Acres 2001, Dell & Rand 2001, Ma 2009).

1.4 COMPONENTS OF SOFC

The basic components of a SOFC, is the anode, the cathode and the electrolyte. The efficiency of a SOFC depends largely on certain features of these materials. The electrolyte should be dense (gas-tight) in order to separate the oxidant and fuel gases, and on the contrary, the anode and the cathode should be porous in order to allow the gas transport to the reaction sites.
Additionally these materials should also exhibit stability in oxidizing and/or reducing environments, chemical compatibility with other components and conductivity. Table 1.1 summarizes the state of the art materials used up to date in SOFC.

**Table 1.1 Materials used in SOFC and their relevant Properties**
(Source:https://www.utwente.nl/tnw/ims/people/formerMSc/Arjen%20Giesbers.pdf)

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
<th>Specific Ionic Conductivity at 1000°C</th>
<th>Specific Electronic Conductivity at 1000°C</th>
<th>Conductivity Depends on</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anode</strong></td>
<td>Ni/YSZ</td>
<td>-</td>
<td>400-1000 S/m</td>
<td>Ni/YSZ particle size ratio; Ni content</td>
</tr>
<tr>
<td><strong>Cathode</strong></td>
<td>La$_{1-x}$Sr$<em>x$MnO$</em>{3-δ}$</td>
<td>$10^{-8}$-$10^{-7}$ S/m</td>
<td>6-60 S/m</td>
<td>Porosity; Sr content</td>
</tr>
<tr>
<td><strong>Electrolyte</strong></td>
<td>Y$_2$O$_3$ZrO$_2$</td>
<td>180 S/m</td>
<td>10-15 S/m</td>
<td>Density; Yttria Content</td>
</tr>
</tbody>
</table>

The materials referred are used in the so-called High Temperature SOFC operating at around 1000°C. The high operating temperature of these systems has certain disadvantages, such as degradation of the material at these high temperatures and the high operating cost of the system.

These two main drawbacks led to the investigation for the development of new materials that reveal high ionic conductivity and stability at lower temperatures.
1.4.1 Anode

The role of an anode in SOFC is electro-oxidation of fuel by catalyzing the reaction, and facilitating fuel access and product removal. Therefore, the requirements for SOFC anode materials are good chemical and mechanical stability in reducing environment, high ionic and electronic conductivity, porous structure and good chemical and thermal compatibility with electrolyte and interconnect materials, high surface oxygen exchange kinetics and good catalytic properties for the anode reactions etc (Goodenough & Huang 2007, Sun & Stimming 2007, Tao & Irvine 2004, Gorte et al. 2002).

The traditional anode of SOFCs is a “cermet” made of metallic nickel and solid electrolyte skeleton, such as Ni-Yttria stabilized zirconia (Ni-YSZ), Ni-Samarium doped ceria (Ni-SDC) (Zhu & Deevi 2003). The electrolyte serves to inhibit sintering of the metal particles and provides a thermal expansion coefficient comparable to that of the electrolyte. However, direct exposure of hydrocarbon fuels to the conventional nickel based anodes has been problematic due to their high catalysis for hydrocarbon cracking reactions at the operating temperatures, leading to carbon accumulation in the anode and thus eventually degrading the cell performance (Koh et al. 2002). The anode has a high porosity (20–40%) allowing mass transport of reactant and product gases is not inhibited. The conductivity of the anode depends on its microstructure, in particular the size and particle size distribution of the solid electrolyte and nickel particles, and the connectivity of the nickel particles in the cermet.

There is a growing interest in developing ceramic anodes as alternatives to cermets (Atkinson et al. 2004). Recently lanthanum-substituted strontium titanate (La-SrTiO₃) with nominal oxygen over-stoichiometry has
been studied and shown to have very high electronic conductivity and methane oxidation catalytic activity (Ruiz-Morales et al. 2006). Alternative anode materials, i.e. replacing nickel by copper in the cermet anode, were thus developed since copper does not catalyze the cracking process (Park et al. 2000).

1.4.2 Cathode

In SOFCs, the cathode functions as the site for the electrochemical reduction of oxygen. To this effect, the cathode must have: high electronic and ionic conductivity; a matched Thermal Expansion Coefficient (TEC) and chemical compatibility with the electrolyte and interconnect materials; adequate porosity to allow gaseous oxygen to readily diffuse through the cathode to the cathode/electrolyte interface; stability under an oxidizing atmosphere; and high catalytic activity for the oxygen reduction reaction (Tietz et al. 2007, Jiang 2006, Vohs & Gorte 2009).

Extensive research is focused on the cathode materials. Numerous doped oxides have been studied as cathode materials for SOFC. Strontium-doped lanthanum manganite (LSM), \( \text{La}_{1-x}\text{Sr}_x\text{MnO}_3 \) is the most commonly used cathode material for YSZ based SOFC (Mogensen & Skaarup 1996).

Another perovskite material that has been extensively studied as a cathode material for SOFC is doped lanthanum cobaltite, \( \text{LaCoO}_3 \) (Ohno et al. 1981). The conductivity of these materials can be increased by substituting cations on the lanthanum and cobalt site. \( \text{La}_{1-x}\text{Sr}_x\text{Co}_{1-y}\text{Fe}_y\text{O}_{3-\delta} \) (LSCF) has been identified as promising materials in terms of both ionic and electronic conductivity (Adler et al. 1996).
Furthermore, there are a number of new materials that have been proposed as cathode materials for SOFC operating at lower temperature. These include perovskite-type materials \([(\text{Sm}, \text{Sr}) \text{CoO}_3, (\text{Ba}, \text{Sr})(\text{Co}, \text{Fe}) \text{O}_3-\delta]\), layered perovskite-related structures \((\text{La}^{n+1}\text{Ni}_n\text{O}_{3n+1})\) and double perovskites \((\text{GdBaCoO}_{5+\delta})\), all of which have shown promising performance at lower temperatures (Skinner 2001). A good electrochemical activity in contact with Ce(Re)O\(_{2-\delta}\) is pointed out with \(\text{La}_{0.8}\text{Sr}_{0.2}\text{Fe}_{0.8}\text{Co}_{0.2}\text{O}_{3-\delta}\) and \(\text{LaFe}_{0.5}\text{Ni}_{0.5}\text{O}_3-\delta\), and \(\text{LaCoO}_3-\delta/\text{La}_2\text{Zr}_2\text{O}_7\).

### 1.4.3 Electrolyte

The electrolyte is the primary component of importance for SOFC (Steele 2000). An ideal SOFC electrolyte should have the following characteristics: high ionic conductivity; low electronic conductivity; good thermal and chemical stability in relation to the reactant environment and the contacting electrode materials; closely matched thermal expansion coefficient (TEC) between the electrodes and contacting components; fully dense structure to maximize conductivity and minimize reactant cross-over; be low cost and environmentally benign (Yokokawa et al. 2005, Goodenough 2003, Fergus 2006, Kharton et al. 2004).

Currently fluorite structure materials, such as zirconia-based and ceria-based oxide, and perovskite \(\text{LaGaO}_3\) based materials are widely used as electrolytes for SOFC. Yttria Stabilised Zirconia (YSZ) is the most widely used electrolyte for SOFCs and possesses good chemical and physical stability as well as negligible electronic conductivity. Addition of 8 mol% of yttria i.e. \((\text{ZrO}_2)_{0.92}(\text{Y}_2\text{O}_3)_{0.08}\) (8YSZ) has the highest oxide ion conductivity. Scandia Stabilized Zirconia (SSZ) also attracts some attention due to its improved conductivity.
Solid electrolytes based on doped cerium dioxide Ce(Re)O$_{2-\delta}$ (Re: rare-earth or alkaline-earth cations) are of considerable interest for potential use in SOFC due to the higher ionic conductivity with respect to stabilized zirconia at temperatures between 500-800°C. Doped Cerium Oxide (DCO), with fluorite structure, is considered to be a promising electrolyte for low temperature SOFC (Steele 2000, Inaba & Tagawa 1996). Samarium Doped Ceria (SDC) and Gadolinium Doped Ceria (GDC) are the most extensively studied ceria based electrolytes, with the maximum ionic conductivity occurring at 10–20 mol% dopants at 500°C.

Compared to YSZ, DCO has a high conductivity and lower activation energy at 500°C. However, DCO suffers from the partial reduction of Ce$^{4+}$ to Ce$^{3+}$ in reducing atmosphere and at high temperature (>600°C), which leads to undesirable structural change, as well as electronic conductivity which reduces performance due to electronic leakage currents between the anode and cathode. Therefore, the operation of SOFCs with a DCO electrolyte is considered most effective in the 500°C temperature.

Perovskite is another type of oxygen ion conductor. Oxides with the perovskite structure are one of the most versatile classes of solid oxide materials. Until now lanthanum gallate is the most widely studied perovskite conductor that is stable in air and hydrogen (Feng & Goodenough 1994, Ishihara et al. 1998, Ishihara et al. 1994). Perovskites can be doped to generate extrinsic vacancies. For example, Lanthanum gallate (LaGaO$_3$) with strontium doping on the A-site of the perovskite and magnesium on the B-site could be used at temperatures as low as 500°C (Ishihara et al. 1994, Ishihara 2003).

A favored composition in terms of ionic conductivity is La$_{0.9}$Sr$_{0.1}$Ga$_{0.8}$Mg$_{0.2}$O$_{2.85}$ (LSGM). However, LSGM is substantially more
expensive than ceria based electrolytes, and it has also proved difficult to prepare pure single phase electrolytes of LSGM. Besides, challenges of matching the thermal expansion coefficients, mechanical strength, and chemical compatibilities need further development.

More detailed review of electrolytes for SOFC is discussed in the next chapter.

1.5 CURRENT CHALLENGES OF SOFC

High Temperature SOFC (HT-SOFC), which operates in the temperature region of 800–1000°C, has been successfully demonstrated by developers such as Siemens Westinghouse and Rolls-Royce (Singhal & Kendall 2003). However, this high temperature presents not only material degradation problems, but also technological complications and economic obstacles (Stambouli & Traversa 2002, Steele & Heinzel 2001).

From standpoint of costs, expensive high temperature alloys are used to house the cell, and expensive ceramics are used for the interconnections, thus increasing the cost of the SOFC substantially (Stambouli & Traversa 2002).

Besides, material degradation is another critical issue prohibitive for broad commercialization. For example, the high operating temperature leads to sintering of the nickel particles, which deteriorates the anode porosity and catalytic activity (Simwonis et al. 2000).

Therefore, reducing the operation temperature of SOFC to the so-called Intermediate Temperature (IT) range of 500–800°C is a grand challenge in SOFC field (Sammes 2004, Huijser & Schoonman 2005, Brett et al. 2008).
1.6 DEVELOPMENT OF INTERMEDIATE TEMPERATURE SOFC

The development of Intermediate Temperature SOFC (IT-SOFC) is now a global tendency for SOFC commercialization. By lowering the temperature of operation, a wider range of materials can be used which allows cheaper fabrication, particularly in relation to interconnect and structural components.

Lower temperature operation offers more rapid start-up and shut-down, reduced corrosion rate of metallic components, more robust construction through the use of compressive seals and metallic interconnects as well as the advantage of greatly simplified system requirements.

A lower operating temperature also ensures greater overall system efficiency and a reduction in the thermal stresses in the active ceramic structures, leading to a longer expected lifetime of the system (Sammes 2004, Huijser & Schoonman 2005, Brett et al. 2008).

Although there are a lot of advantages of Intermediate Temperature Fuel Cells (IT-SOFCs), there is a coming major challenge. As the operating temperature decreases, the ionic conductivity of the Traditional Electrolyte (YSZ) decreases exponentially and the ohmic loss of electrolyte becomes considerable. When temperature is lowered from 800 to 500°C, the ionic conductivity is reduced by nearly three orders of magnitude. To be applied in SOFCs, a minimum requirement of ionic conductivity is $10^{-2}$ S/cm.

Therefore, the Traditional Electrolyte Material (YSZ) cannot fit this request. So, recently the key point of IT-SOFCs research is to develop suitable electrolyte materials. There are two main strategies to overcome the
problem with SOFC operated at lower temperatures, while still supplying sufficient ionic conductivity of electrolyte and attaining performance comparable to the higher temperature technology.

First, the dimensional thickness of the electrolyte can be reduced by developing various physical or chemical thin film technologies for SOFC, such as electrophoretic deposition, spin coating method, radio-frequency sputtering, atomic layer deposition and pulsed laser deposition, for reducing the area specific resistance of the fuel cell in order to decrease the operation temperature (Beckel et al. 2007, Chen & Wei 2006, Hosomi et al. 2007, Huang et al. 2007, Shim et al. 2007).

There are several advantages on synthesizing SOFC electrolyte components by thin film processes, e.g. ohmic losses can be reduced, sintering temperature can be decreased and interfaces can be easily controlled. However, there are still some drawbacks in this method, such as long production period, very high cost, difficulty on scaling up, as well as difficulties on control of film growth, which make it difficult to realize the commercialization of IT-SOFC.

Second, exploring and developing new electrolyte materials with higher ionic conductivity by nanotechnology approach or composite approach, which can also reduce the area specific resistance at lower temperatures and bring about improvements in the performance of electrolyte materials with enhanced ionic conductivity. Both the approaches have their own advantages and drawbacks.

In nanotechnology approach the conductivity of micro-sized polycrystalline electrolyte is contributed to both grain-interior and grain-boundary. The specific grain-boundary resistivity is known to be two to three
orders of magnitude higher than the grain-interior resistivity. This blocking effect comes from the oxygen vacancy depletion near the grain-boundary (Guo et al. 2002). Therefore, many efforts have been taken on the engineering of grain-boundary to lower its resistance, and improve the performance of polycrystalline electrolytes.

However, ion transport across or along grain boundaries in solids with nanometer-sized grains may differ distinctly from that in conventional polycrystalline solids (Guo et al. 2002, Tuller 2000). In recent years, the enhancement of ionic conductivity in the nanostructured solid electrolytes, known as “nanoionics”, (Maier 2005, Despotuli & Nikolaichik 1993) has been rapidly recognized as an emerging new scientific area and widely applied on rechargeable lithium-ion batteries, gas sensors and solid oxide fuel cells (Arico et al. 2005).

Some works have been done to study the enhanced oxide ion conductivity of nanostructured electrolyte for SOFCs. The total ionic conductivity of nanostructured, doped ceria solid electrolyte increases about one order of magnitude compared to microcrystalline materials (Bellino et al. 2006). Using ceria-based materials, the operating temperature can be much lowered creating a big breakthrough in IT-SOFCs field.

1.7 OBJECTIVES AND METHODOLOGY

In order to develop IT-SOFCs, there are two ways to implement the aim: first, the dimensional thickness of the electrolyte can be reduced by developing various physical or chemical thin film technologies for SOFC; second, to decrease the area specific resistance of cells by developing new electrolyte materials with higher ionic conductivity.
Therefore for this research the second way was selected with an objective to explore new electrolyte material for SOFCs with increased ionic conductivity. As ceria-based material has been investigated as a promising electrolyte for IT-SOFCs and has shown a higher ionic conductivity and improved fuel cell performance, it was decided to make use of doped ceria in order to reduce the operating temperature of SOFCs at 500°C.

But, from the literatures it was seen that low temperature operations are mostly not suitable for singly doped ceria due to higher electrical resistance. Hence, structural modifications of ceria-based solutions have to be made by co-doping of the elements to increase the oxide ionic conductivity of ceria–based electrolytes in the intermediate temperature range below 600°C. Research reviews also show that co-doped ceria electrolytes could improve the ionic conductivity of IT-SOFC than singly doped ceria. Hence, the present research focuses on the development of Magnesium and Scandium co-doped ceria to be used as electrolyte for IT-SOFC at 500°C.

Co-precipitation method was used to prepare pure Ceria, Magnesium doped Ceria and Scandium doped Ceria samples. Required quantities of Cerium nitrate hexahydrate (Ce(NO$_3$)$_3$·6H$_2$O) (99.99%, Himedia), Magnesium nitrate hexahydrate (Mg(NO$_3$)$_3$·6H$_2$O) (99%, Himedia) and Scandium nitrate hexahydrate (Sc(NO$_3$)$_3$·6H$_2$O) (99%, Himedia) were used as starting materials. All the chemicals are of analytical grade and were used as purchased.

For pure ceria, Cerium nitrate hexahydrate was dissolved in 80% ethylene glycol/water mixed solvents and for Magnesium doped ceria, 0.1M of Cerium nitrate hexahydrate and 0.1M of Magnesium nitrate hexahydrate was mixed according to the desired molar ratio of Ce$_{1-x}$Mg$_x$O$_2$ (CMO) with a metal loading of $x = 0, 0.5, 0.1, 0.15$ and $0.2$. Similarly for Scandium doped ceria, 0.1M of Cerium nitrate hexahydrate and 0.1M of Scandium nitrate
hexahydrate was mixed according to the desired molar ratio of $\text{Ce}_{1-x}\text{Sc}_x\text{O}_2$ (CSO) with a metal loading of $x = 0, 0.5, 0.1, 0.15$ and 0.2. The required reagents were also mixed in distilled water in order to prepare co-doped ceria based materials (CMS) with the formula $\text{Ce}_{1-x}(\text{Mg}_{0.5}\text{Sc}_{0.5})_x\text{O}_2$ ($x=0-0.24$).

All the components were dissolved in distilled water using a magnetic stirrer at 80°C with a stirring rate of 500 rpm. Ammonium hydroxide (NH$_4$OH) was added drop-wise to this mixture. The mixed solution was stirred continuously until the reaction is completed in about 12 hours after which the precipitates were centrifuged and washed with water and ethanol multiple times. The synthesized powders were dried and calcinated at 800°C for about 24 hours in air atmosphere to obtain nanocrystalline form of pure and doped ceria samples.

These nanocrystalline forms of powders were then subjected to different characterization techniques to test its phase identification. The powders were ground and then cold pressed isostatically under 4000 kg/cm$^2$ to form pellets with 0.1 cm thickness and 1.0 cm diameter which were further sintered in air at 1500°C for 2 hours. These pure, singly doped and co-doped ceria pellets were used for electrical measurements.

The phase analyses of the sintered samples were identified by X-Ray Diffraction (XRD) analysis by using Philips X-ray diffractometer PW 1830. The crystalline sizes of the powders have to be estimated by the line broadening analysis, using the reflection planes. The morphology and composition of the nanocrystalline form of the samples have to be subjected to Scanning Electron Microscopy (SEM) using a JSM-6335F, JEOL microscope. The electrical properties of the samples were investigated by ac impedance spectroscopy at 500°C temperature and at the frequencies from 50Hz to 5MHz using an impedance analyzer HIOKI 3532.
In this research pure ceria, singly doped ceria and co-doped ceria with Mg and Sc in desired proportions were compared based on the ionic conductivity through impedance results so as to find out the composition giving highest ionic conductivity at 500°C temperature which will be suitable as an electrolyte for IT SOFC. Further by using co-doped ceria as the electrolyte, a fuel cell was fabricated with a Ni anode and a La$_{0.6}$Sr$_{0.4}$Co$_{0.2}$Fe$_{0.8}$O$_3$ composite cathode. Its performance was compared with that of singly doped ceria and 8YSZ electrolyte based fuel cells.

1.8 OUTLINE OF THE THESIS

Chapter 1 is an introductory chapter to fuel cells. The fundamentals of Solid Oxide Fuel Cell are discussed in detail in this chapter.

Chapter 2 is referring to literature review of other types of fuel cells, fuels used for fuel cells and what has been done up to date specifically on SOFC electrolyte materials by different research groups. Also a brief description about the different synthesis routes and different characterization techniques are pointed out.

In chapter 3 and Chapter 4 a detailed discussion of the synthesis and characterization that has been followed during this research for singly doped ceria and co-doped ceria to be used as an electrolyte for ITSOFC is being done.

In chapter 5 a detailed comparison of the performances of fuel cells fabricated with co-doped ceria, singly doped ceria and 8YSZ electrolyte has been made.

Chapter 6 gives the conclusion of research and suggestions regarding future work.