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13. ABSTRACT (Maximum 200 words) Ca-substituted YIG single crystal films (Ca:YIG) show <i>p</i>-type conduction while Si or Ge doped YIG garnets (Si:YIG or Ge:YIG) have <i>n</i>-type conduction. Both garnet films maintain their superior magnetic properties of pure YIG, while their electrical resistance approaches that of a semiconductor. Bilayers of Si/Ca doped YIG film were grown as a <i>p/n</i> junction and found to have significant <i>p/n</i> junction diode behavior. However, a voltage of 60 to 80 volts is required to observe a significant contribution to the asymmetry. The details of the I-V curves were also found to depend on the thickness of the Ca:YIG underlayer and the position of the contacts. In the Ca:YIG films a very sharp drop in the resistance was observed between 0 and ± 5 G. At zero volts the resistivity was on the order of 1000 ohm\cdotm and at ± 5 G it is reduced to 2 ohm\cdotm a surprising result. Since the conclusion of this work, a significant magneto resistance of a few percent has also been observed in the Ca:YIG films.					
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**Uncompensated Garnet -
A Magnetic Semiconductor**

Final Report

**Principal Investigator
P. E. Wigen**

October 1998

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Body of Report

1. Introduction

Ca-substituted YIG single crystal films (Ca:YIG) show *p*-type conduction and Si or Ge doped YIG garnets (Si:YIG or Ge:YIG) have *n*-type conduction. Both garnet films maintain the superior magnetic properties of pure YIG, while their electrical resistance approaches that of a semiconductor. Therefore, these materials have the potential to be magnetic semiconductors. The doped YIG films are grown by liquid phase epitaxy (LPE) under special conditions developed in this laboratory and the lower resistivities of doped YIG films have been produced [1,2]. As a result, the potential of bilayer Si/Ca doped-YIG film as a magnetic p/n junction has been studied in the past twelve months.

2. Electrical measurement for Ca, Si, and Ge:YIG films

The new LPE growth method produces Ca:YIG, Ge:YIG, and Si:YIG films having resistivities on the orders of 10, 10^3 , and 10^4 Ωcm , respectively. The resistivity of Ca:YIG reduces almost 3 orders as the applied voltage varies from 0.1 to 2 volts (see fig. 1), while the changes resistivities of Ge:YIG and Si:YIG over the voltage range investigated are less than 10% (see fig. 2). Figures 3a and 3b indicate that with Indium or gold contact the I-V characteristic for the *n*-type doped Si:YIG or Ge:YIG film is ohmic over

the whole voltage range. The behavior in Ca:YIG films can be divided into three different regions as observed in figure 4; an ohmic region at low applied voltages (below 1 volts), an intermediate region (1-20 volts) having a quadratic dependence, and the high applied voltage region (greater than 20 volts) where the behavior is again ohmic [3]. These effects have been investigated and reported in detail in the dissertation of Turpin [4].

3. New LPE Sample Growth

During the recent investigation, it has been observed that the growth rate of YIG LPE films was not constant. The longer the growing time, the slower the growth rate. No significant change in the thickness was observed after 15 minutes dipping in the melt. The growth rate influences the conductivity of the doped YIG by changing the density of impurities [5]. To investigate these effects in detail, three different bilayer Ca:YIG films were made on a one-inch (111) GGG substrates. The first layer of each film is the same having a 12-minute deposition time. The substrates were then removed, cleaned and a second layer was grown with growth times varying from 4, 8 to 12 minutes. The thickness of Ca:YIG layer is measured by using a scanning electron microscope (SEM). Indium electrodes were placed on the three samples, and heated up to 250 °F for 15 minute to reduce non-

ohmic contact. From the electrical measurements shown on figure 5, it can be concluded that the lower growth rate gives the higher resistivity.

The resistivity of Si:YIG was found to be three to four orders of magnitude larger than that of Ca:YIG, where Ge:YIG is only two to three orders of magnitude larger. As a result, germanium will be chosen as the tetravalent substitution to produce the *n*-type YIG in future studies [5]. With future developments of the growth techniques in germanium doped YIG films a decrease in the resistivity similar to that developed in Ca:YIG is expected.

4. The new method to get P/N junction Diode in Garnet

The horizontal dipping techniques was used to produce Ca/Si:YIG bilayer films (see fig. 6). One of the difficulties with the bilayer film was making a proper electrical contact to the underlayer. To test the p/n junctions, a new phosphoric acid etching method has been developed to replace the previous method of physically grinding a hole through the upper layer with a dimpling machine. The top surface of each sample was partially covered by a gold layer whose thickness is about 3000Å. Gold was used because of its inherent insolubility to hot phosphoric acid and thereby protects the masked region of the sample from etching. When the samples are put into 80% phosphoric acid, the uncovered part of other Si:YIG film is

etched off [6]. Since consecutive etching was required the electrode on the etched layer must be removed, for this reason indium was used to contact the exposed *p*-type Ca:YIG film. The configuration of the electrodes is shown in figure 6.

5. Electrical measurement of the P/N junction Diode in Garnet

Upon increased etching of the Ca:YIG layer, for positive voltage applied from the *p*-type Ca:YIG underlayer to the *n*-type Si:YIG surface layer, the resistance of the p/n junction decreased with etching while it increased for the reverse polarity. The 24- μ m etching is the exception shown in figure 7a. While the etching thickness of films influences the diode characteristics, adjusting the gap between the two electrodes on the different doped YIG layers was also found to influence the diode characteristics. Figure 8a indicates that a gap width between 0.08 and 0.4 mm improves significantly the electrical properties of the p/n junction.

Since both the single layer of Ca:YIG and Si:YIG have antisymmetrical I-V behavior as shown in figure 3, the unsymmetrical I-V characteristic of Ca/Si:YIG bilayer films must demonstrate the behavior of a p/n junction diode. To clarify the difference in the unsymmetrical I-V behaviors of Ca/Si:YIG bilayer films, the contribution from the negative voltage side is added to that of the positive voltage side. According to this

model, the Ca/Si:YIG bilayer structure is treated as a p/n junction diode being in parallel with the series combination of the Ca:YIG and the Si:YIG resistors. It also assumes the resistance of a p/n junction diode is infinite for the negative polarity and the resistance of the Ca:YIG or the Si:YIG film is independent of the direction of polarity as shown in figure 3. The resulting I-V curves of the Ca/Si:YIG bilayer films in figures 7b and 8b show a typical p/n diode characteristic.

The relation between etching thickness and the suitable electrode gap for the best behavior of p/n junction diode will be investigated in the next phase of the research.

6. Conclusions

The Ca:YIG film produced by the new LPE growth method shows a very abrupt slope in its R-V curve, where the resistivity reduces by 3 orders of magnitude as the applied voltage just changes between 0.1 and 2 volts (see fig. 1). The Ca/Si:YIG bilayer film has a significant p/n junction diode behavior (see fig. 7 and 8). The details of the I-V curve were found to depend on the thickness of the Ca:YIG underlayer and the position of the contacts. The use of Ge:YIG instead of Si:YIG in the p/n bilayer structure is expected to reduce the total resistance and to produce even better diode characteristics.

List of Publications

G. B. Turpin, and P. E. Wigen, J. Magn. Mat., 235, 177 (1998)

List of Participating Personnel

Two graduate students, and an undergraduate student having received funding through this program in the past year, and a post doctor research associate are currently working on the project of uncompensated Ca:YIG garnet material.

These are:

1. G. B. Turpin (Ph. D. 1997)
2. D-L. Li
3. U. Ebels (Post Doctor)
4. Geoff Prewett (undergraduate)

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- [4] G. B. Turpin, *Resistivity Decay and Electrical Response in Ca-Substituted Yttrium Iron Garnet Thin Films*, (dissertation 1996).
- [5] Taketoshi Hibiya, Yasuharu Hidaka, and Kozaburo Suzuki, *J. Appl. Phys.*, 49, 2765(1978).
- [6] R. W. Patterson and J. D. Adam, *J. Appl. Phys.*, 49, 1888 (1978).

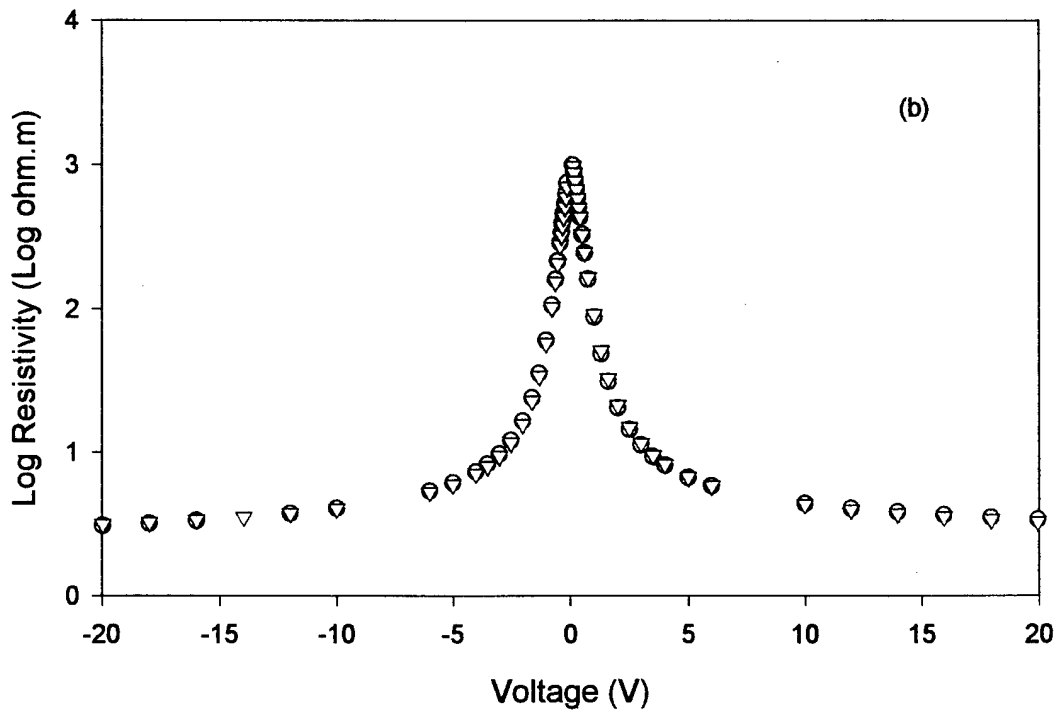
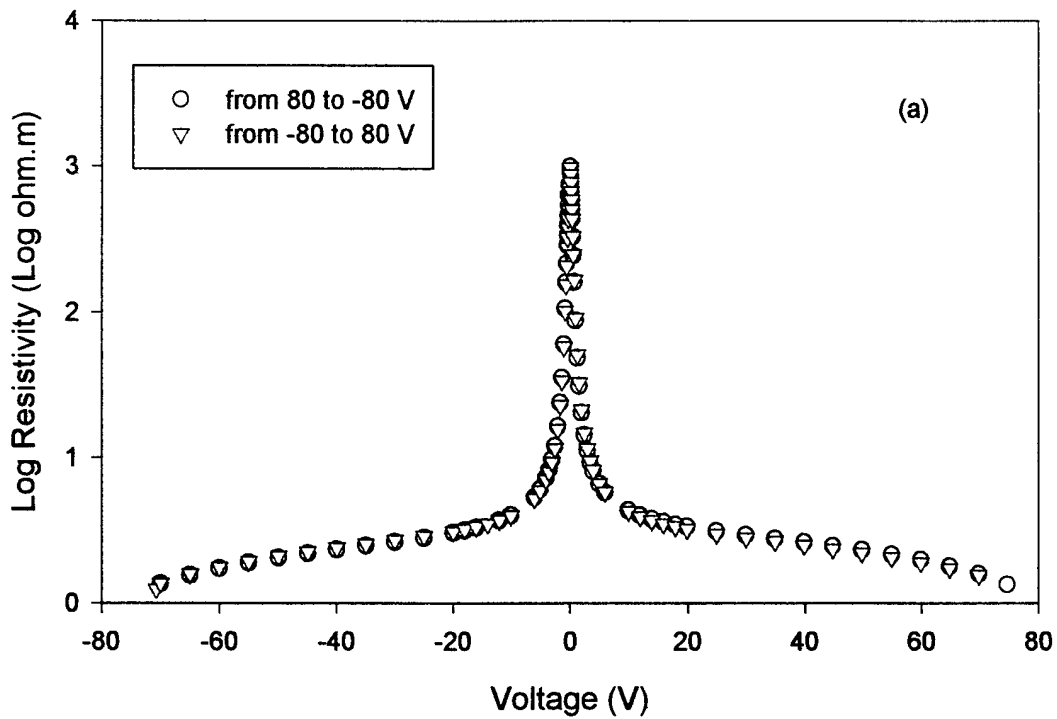


Fig. 1. Resistivity vs voltage loop for a Ca:YIG film showing non-hysteresis characteristic. (a) The magnitude of resistivity dropping 3 orders while increasing voltage from 0 to 80 V; (b) The details of δ -function like R-V characteristic in low voltage range.

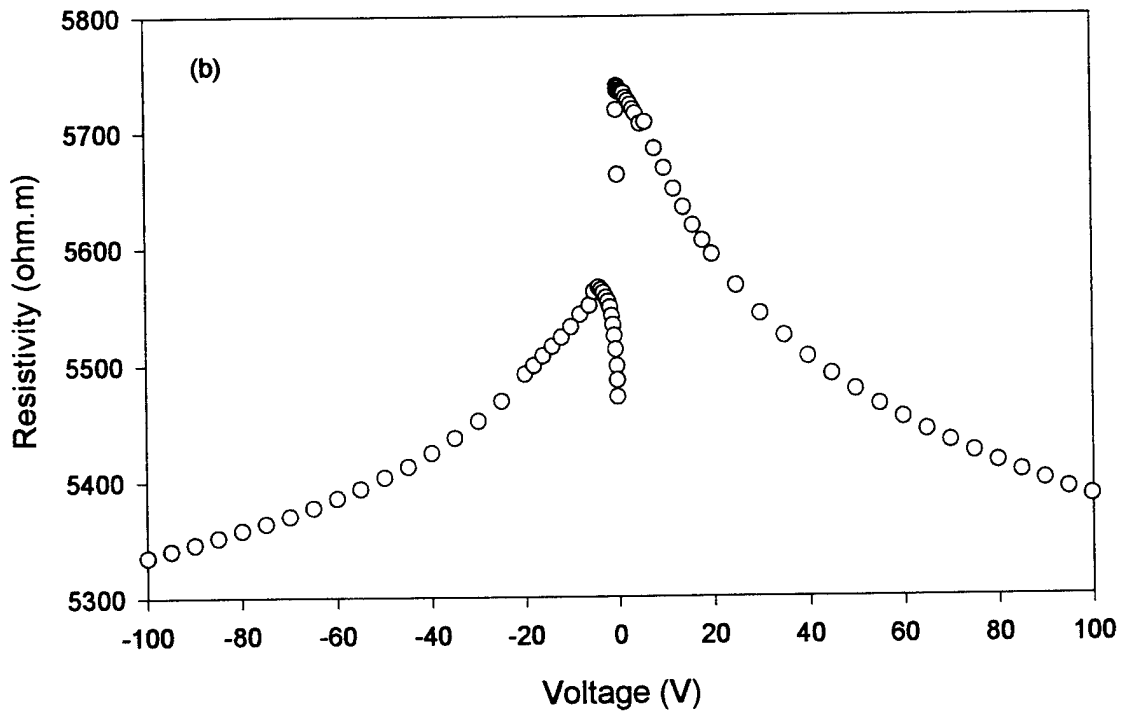
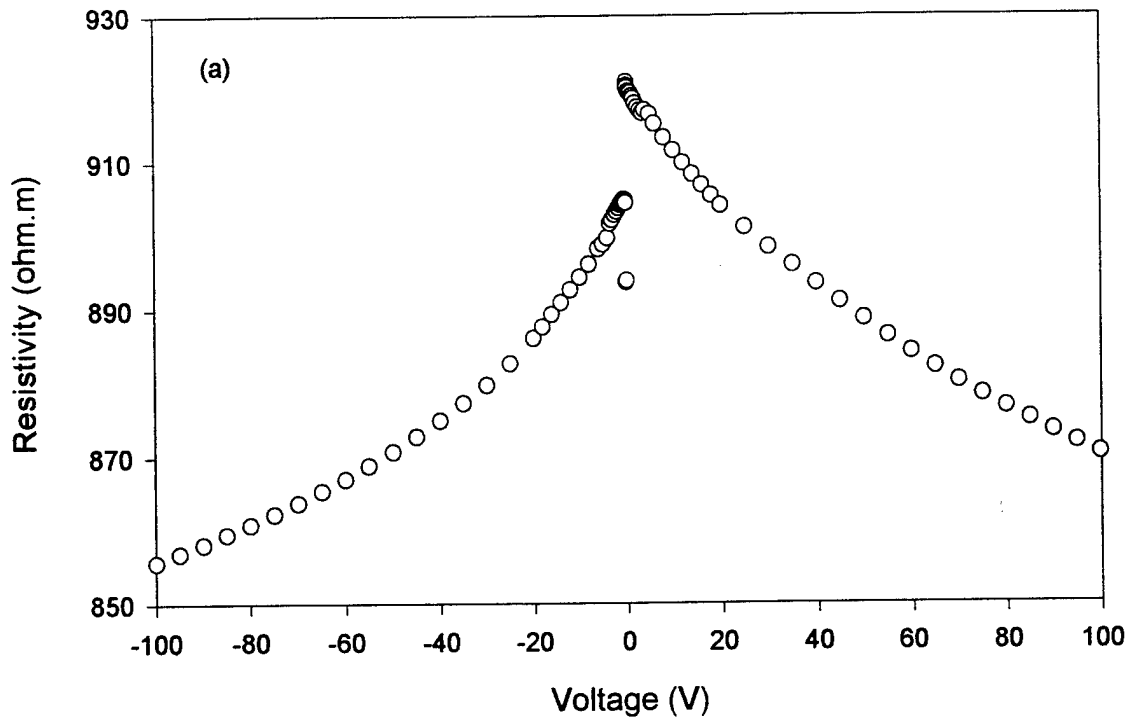


Fig. 2. Resistivities of Ge:YIG and Si:YIG films under voltages from -100 to 100 V. (a) For Ge:YIG, the change of the resistivity is smaller than 8%; (b) For Si:YIG, the resistivity varies within 8%.

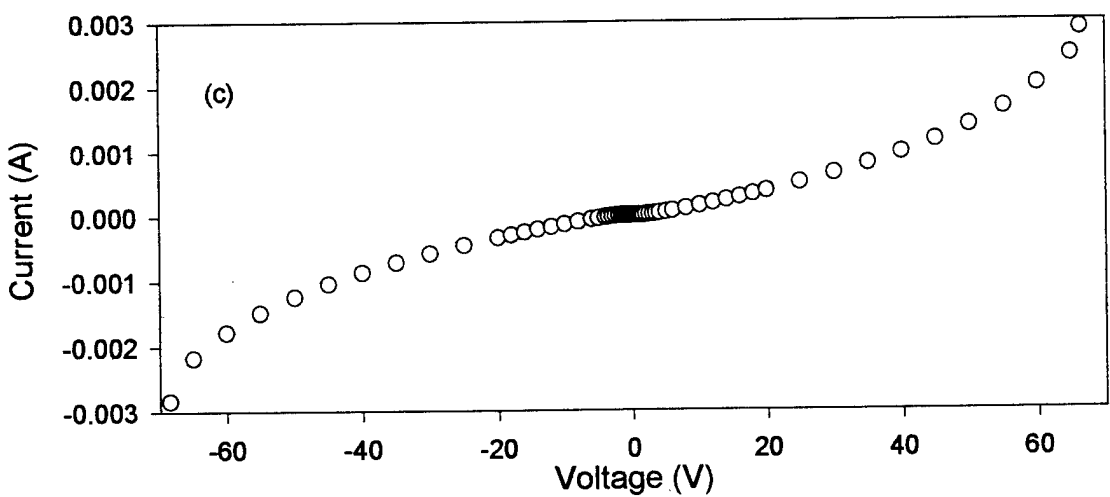
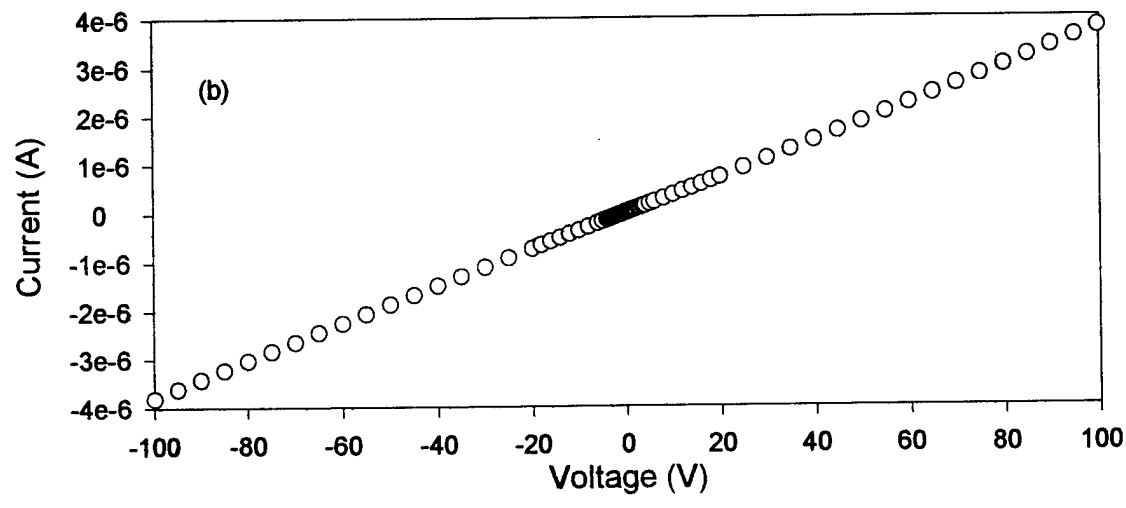
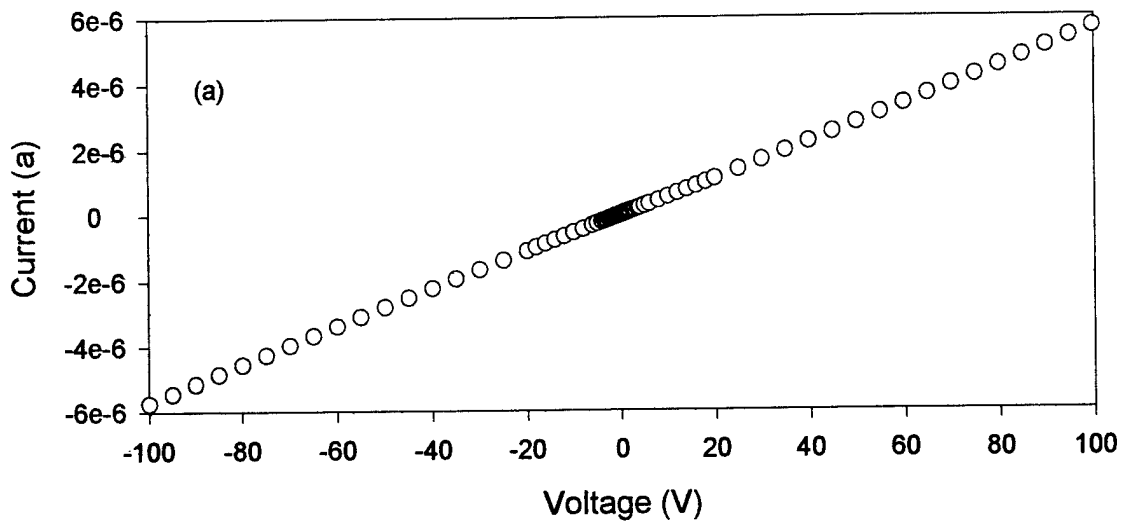


Fig. 3. I-V characteristics for Ge:YIG, Si:YIG, and Ca:YIG films. (a) Ohmic I-V behavior of Ge:YIG film; (b) Ohmic I-V behavior of Si:YIG film; (c) Nonlinear antisymmetrical I-V curve of Ca:YIG film.

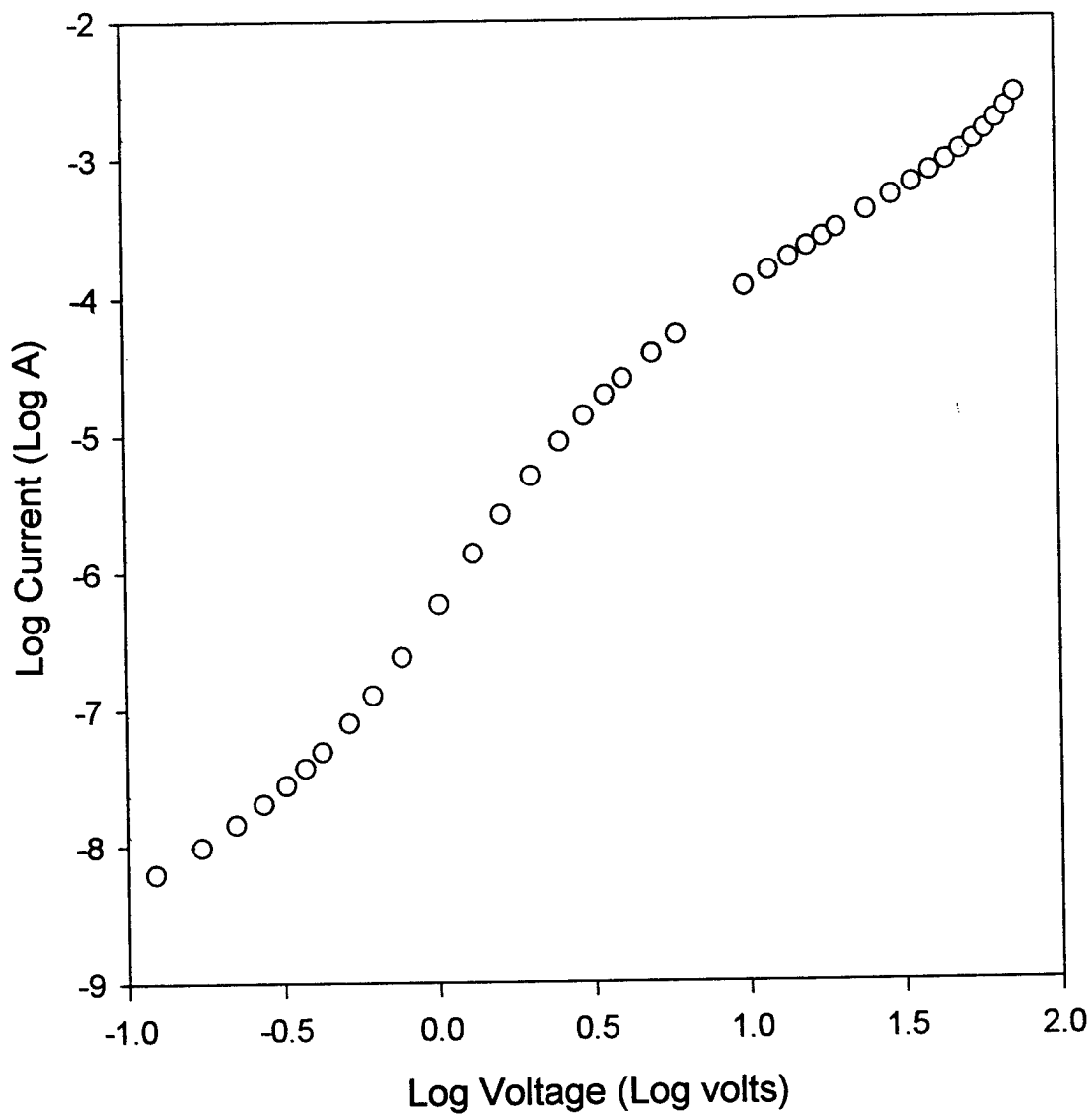


Fig. 4. Log-Log schematic of I-V curve for a Ca:YIG film. Low voltage ohmic range from -1 to -0.25; an intermediate range (0 to 1) having a quadratic dependence; the high voltage ohmic range from 1.1 to 1.8.

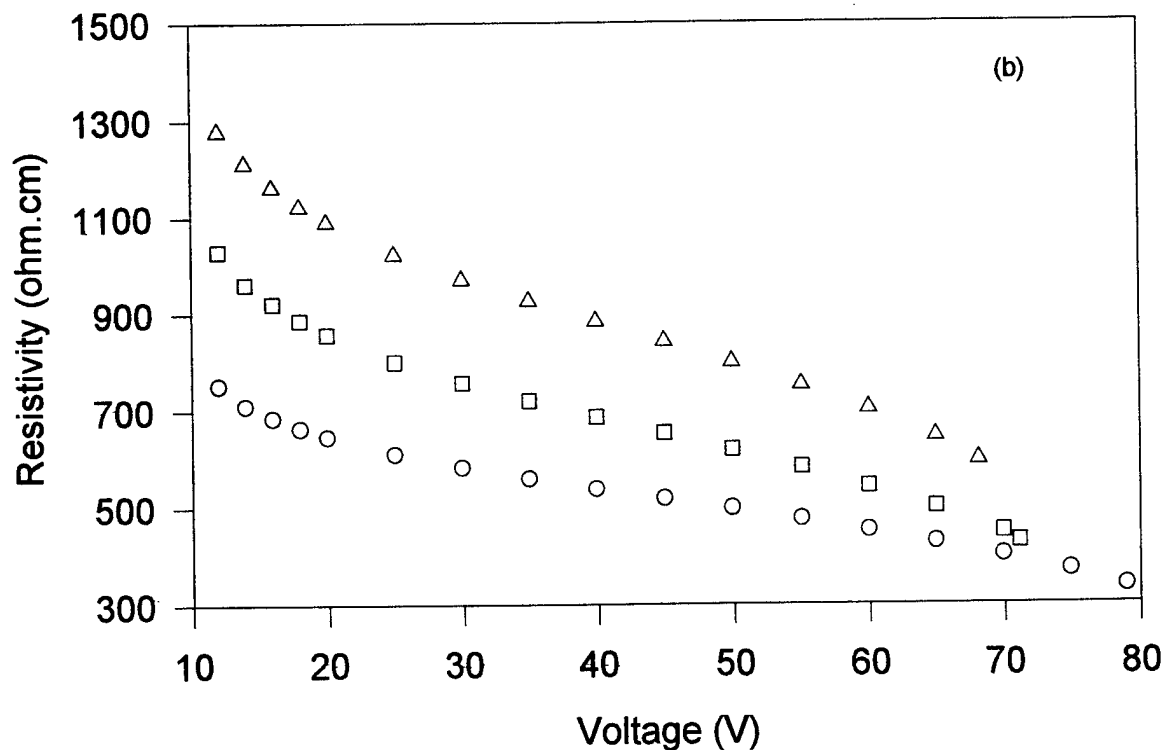
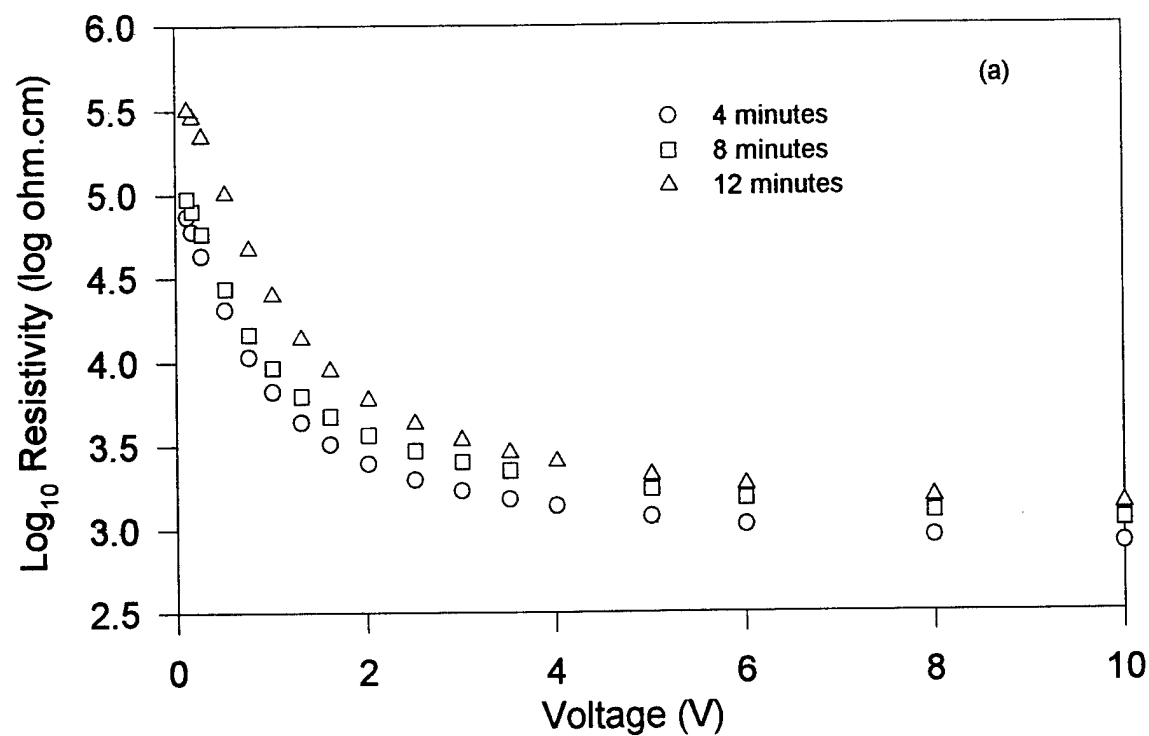


Fig. 5. Schematic of the resistivity vs Voltage for Ca:YIG films under different growth time. (a) Rapid dropping resistivities in the low voltage range (below 10 V); (b) The R-V characteristic in the rest of voltage range.

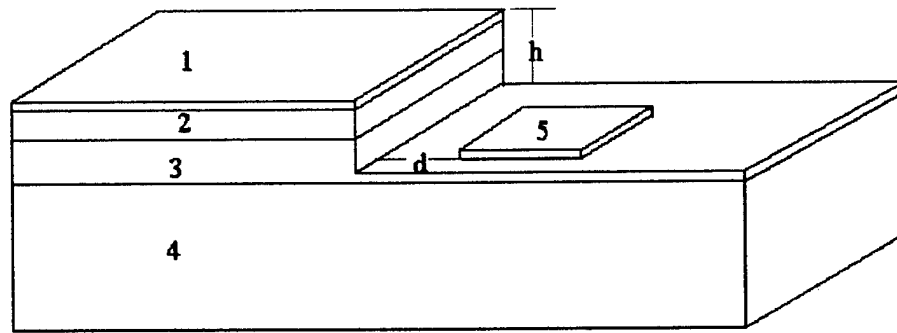


Fig. 6. The geometry of the p/n junction diode. 1--Gold; 2--Si:YIG; 3--Ca:YIG; 4--GGG substrate; 5--Indium; h is the etching thickness; d is the gap between gold and indium electrodes.

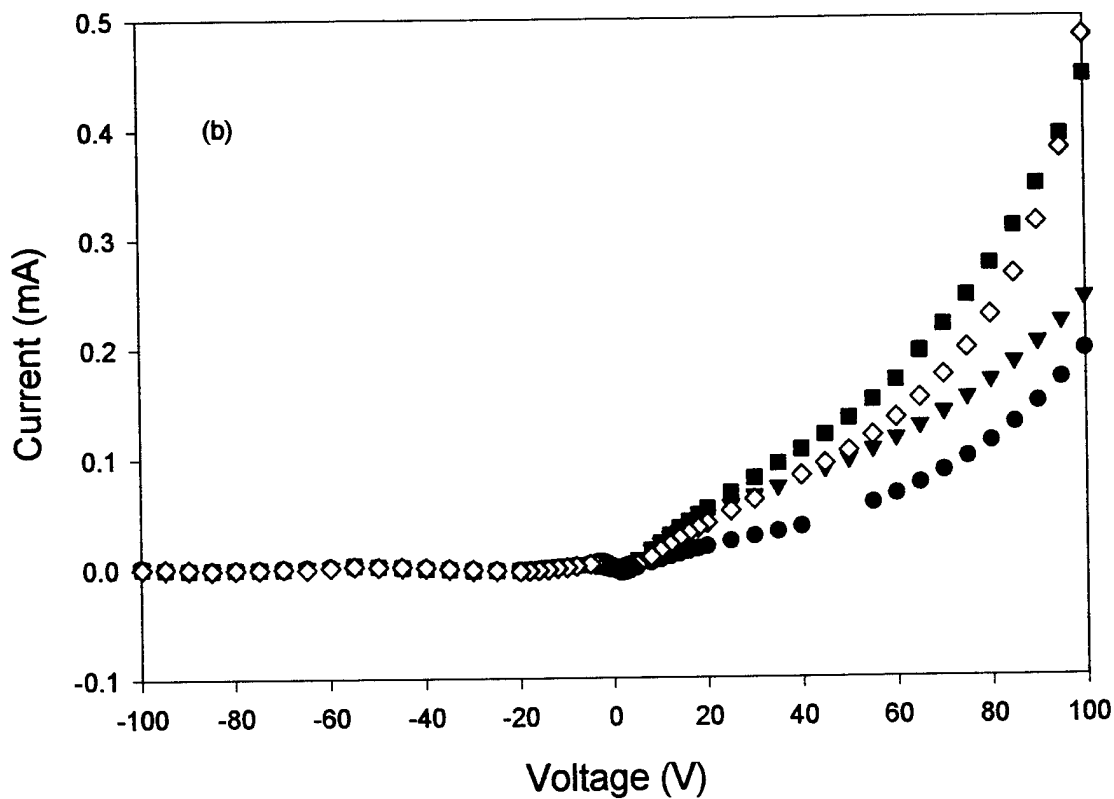
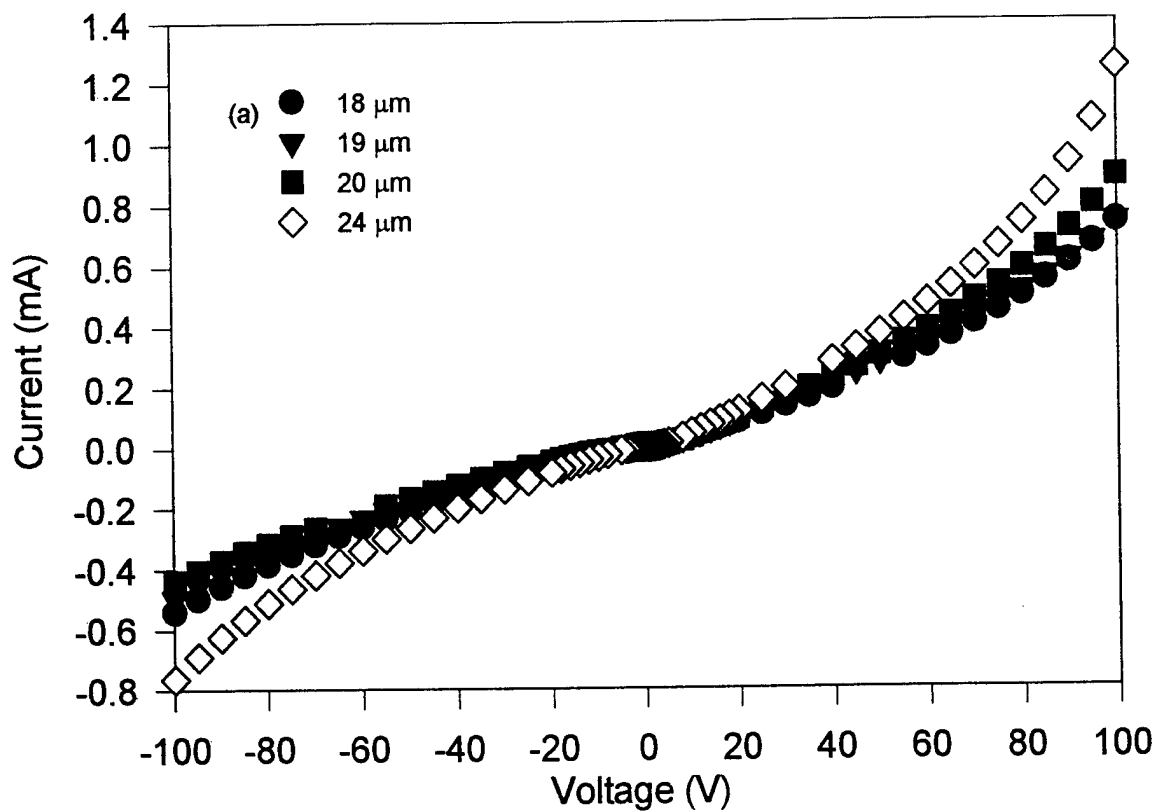


Fig. 7. The etching thickness effect on I-V curve of diode (Gap 0.05mm). (a) Experimental data; (b) The data subtracted symmetrical resistivity contribution from Ca:YIG and Si:YIG films.

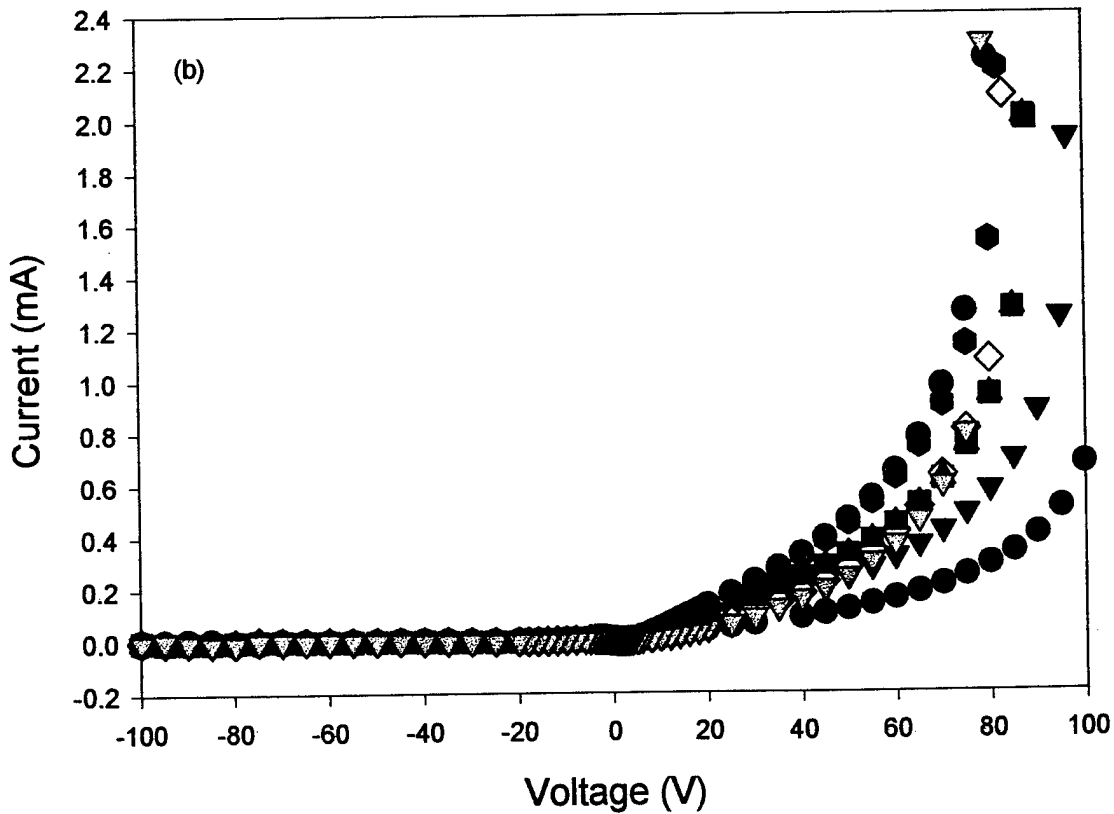
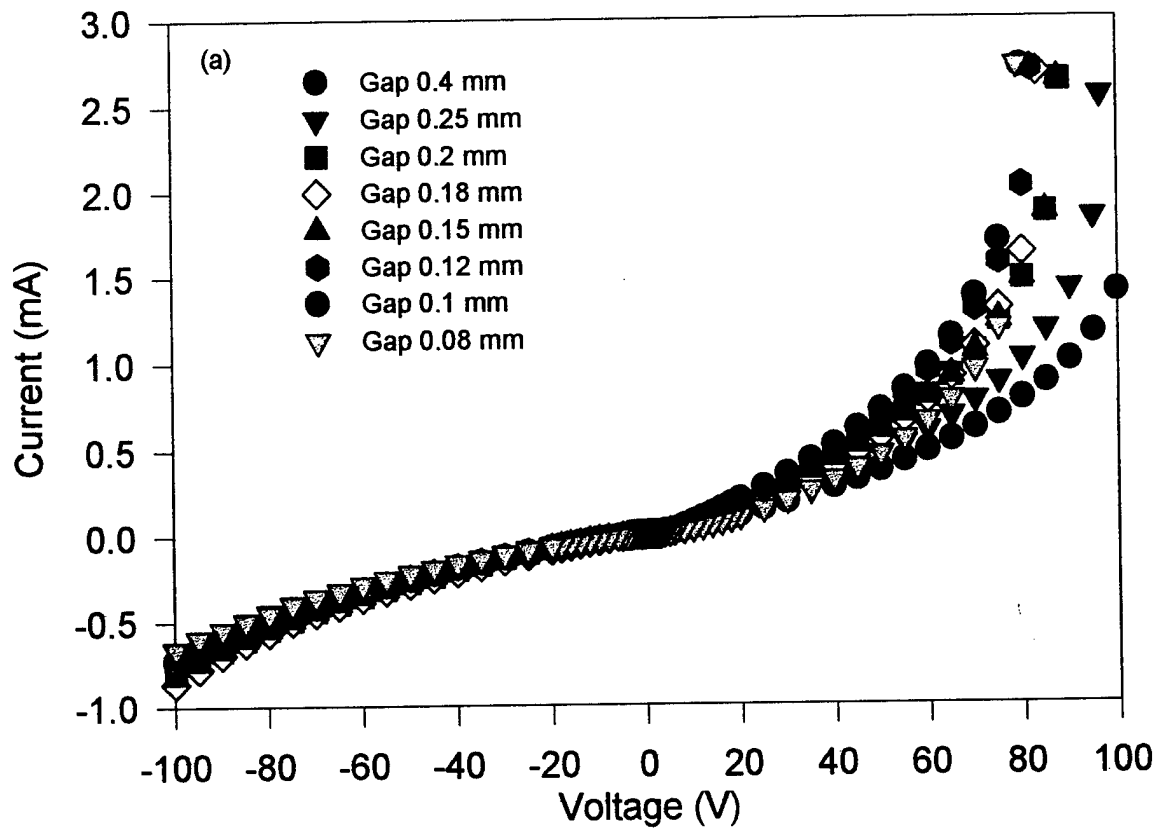


Fig. 8. The I-V curves for different gaps between electrodes on diode (etching $24\ \mu\text{m}$). (a) Experimental data; (b) The data subtracted the electrical symmetric resistivity contribution from Ca:YIG and Si:YIG.