Increase in Electric Conductivity of YbFe_2O_4 under Ar laser Irradiation

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We measured electric conductivity of YbFe_2O_4 poly crystal under Ar (488 nm, 2.54 eV) and He-Ne (632.8 nm, 1.96 eV) lasers. In order to discuss only photoconductive effect, sample temperature was measured during the electric measurement. The electric conductivity increases exponentially with increase of Ar laser intensity in isothermal process, despite that electric conductivity increases proportionately to light intensity in general semiconductor. This abnormal photoconductivity implies exponential increase of number of electric carrier by melt of charge order.

Key words: Electric conductivity, Photoconductive effect, Charge order

1. INTRODUCTION

The strongly correlated electron system has been attracted much attention in solid state physics thanks to its sensitive response to external fields. Rare earth ion ferrite $R\text{Fe}_2\text{O}_4$ ($R = \text{Y, Dy, Ho, Er, Tm, Yb, Lu, Sc, or In}$) is the typical example. This material is composed of doubly stacking Fe triangular layers separated by single R triangular layer [1]. Equal amounts of Fe^{2+} and Fe^{3+} exist on triangular lattices and form charge orders due to the Coulombic interaction between iron ions [2,3]. The electric conductance is realized by electron hopping on Fe^{2+} and Fe^{3+} in the charge order [4].

The charge order is sensitive to electric field, current and light. H. Itoh reported that the charge order melts under light irradiation in 1 ps [5]. We have reported that the electric conductivity increases with increasing applied current, which is likely to be accompanied by melt of charge order [6]. These experimental data suggest that light irradiation increases the electric conductivity by melt of the charge order.

In this work, we measured electric conductivity of YbFe_2O_4 poly crystal under Ar and He-Ne lasers. Most of the energy of He-Ne laser was used to heat the sample. On the other hand, the electric conductivity increased exponentially with increase of Ar laser intensity, despite that electric conductivity increases proportionately to light intensity in general semiconductor. This phenomenon is induced by something other than heating effect and general carrier excitation.

2. EXPERIMENTAL DETAIL

Poly crystal of YbFe_2O_4 was prepared by a solid state reaction method from powders of Yb_2O_3 and Fe_2O_3 . The mixture of CO_2/CO gas was flowed during the sintering. The sample was cut into $4.51 \times 3.78 \times 2.85 \text{ mm}^3$ for the measurements.

Fig. 1 shows the experimental set up. The voltage was measured under constant current (1 mA) in order to reduce the Joule heating. The dc current was applied by YOKOGAWA 7651, and the voltage was measured by GDM-8342. Silver paste was used for electrodes. The measurements were performed at room temperature.

In order to detect the sample heating by current flow

and laser irradiation, sample temperature was measured by thin alumel-chromel thermocouple. The voltage of the thermocouple was measured by Agilent 34410A.

Ar and He-Ne lasers were irradiated to the sample. The beam diameter was 3 mm. Uniphase Ar laser 2213-75SLK (488 nm, 2.54 eV) and Melles Griot He-Ne laser 05-LHP-991 (632.8 nm, 1.96 eV) were used. The laser intensity was measured by optical power meter (ADVANTEST TQ8210).

Fig. 1. Experimental set up for the measurement.

3. RESULTS AND DISCUSSION

The voltage and sample temperature was measured under current flow with Ar and He-Ne laser irradiation. Fig. 2 shows typical example. The laser irradiation raises both of the electric conductivity and sample temperature.

Fig. 2. Reciprocal voltage and sample temperature in current flow (1 mA) under He-Ne laser (8 mW).

Fig. 3 shows the electric conductivity under laser irradiation with different intensity plotted as a function of the sample temperature. The plots for He-Ne laser are on single line even with different laser intensity as shown by narrow pink arrow. This result indicates that the most of the He-Ne laser energy is used to heat the sample. On the other hand, the plots for Ar laser are on individual lines with different laser intensity as shown by blue thick lines. This result indicates that the conductivity increases not only by sample heating but also by electric carrier excitation due to Ar laser absorption.

Fig. 3. Electric conductivities under Ar and He-Ne laser irradiation with different intensity as a function of the sample temperature. The dashed lines and arrows are guide for eye.

In order to discuss the effect of Ar laser irradiation in isothermal process, the conductivity at 297 K is plotted as a function of the intensity of Ar laser in Fig. 4. The data for 8.0 mW and 0.8 mW laser at 297 K are estimated from data at close temperature as shown by red and blue dashed lines in Fig. 3. The conductivity rises exponentially with increase of the laser intensity.

Fig. 4. Electric conductivity as a function of irradiated Ar laser intensity at 297 K.

In general semiconductor, conduction carrier increases under light, accompanied by increase of electric conductivity, if the light has larger energy than band gap of the semiconductor (photoconductive effect). The number of excess carrier (Δn) is proportional to number of photons (N), as described by equation (1) [7].

$$\Delta n \propto N \quad (1)$$

Since the conductivity on dark state (σ_{off}) and that under light (σ_{on}) are given by equations (2) and (3), respectively, the difference in conductivity ($\sigma_{\text{on}} - \sigma_{\text{off}}$) is described by equation (4), where μ is carrier mobility.

$$\sigma_{\text{off}} = e\mu n \quad (2)$$

$$\sigma_{\text{on}} = e\mu(n + \Delta n) \quad (3)$$

$$\sigma_{\text{on}} - \sigma_{\text{off}} = e\mu\Delta n \quad (4)$$

As the laser intensity (W) is given by equation (5), if the laser energy ($h\nu$) is constant, the difference in conductivity is proportional to laser intensity (equation (6)).

$$W = Nh\nu \quad (5)$$

$$\sigma_{\text{on}} - \sigma_{\text{off}} \propto W \quad (6)$$

Contrary to the general semiconductor, the difference in conductivity of YbFe_2O_4 increases exponentially with increase of laser intensity as shown in Fig. 4. This result suggests exponential increase of number of conduction carrier against irradiated laser intensity.

This abnormal electric conductivity under light may be associated with melt of charge order. We have reported that the electric conductivity increases with increasing applied current in isothermal process [6]. The rise of the conductivity is observed only below charge ordering temperature, suggesting the melt of the charge order as a cause of the increase of the conductivity. H. Itoh has reported a melt of the charge order under light irradiation [5]. Therefore, Ar laser is likely to melt the charge order and cause the increase of number of carrier and the conductivity.

However, H. Itoh observed melt of the charge order in LuFe_2O_4 single crystal under 1.55 eV light, while we observed only heating effect in YbFe_2O_4 poly crystal under He-Ne laser (1.96 eV) irradiation. The band gap energy has possibilities to be changed slightly by different rare earth ions, as they change physical parameters slightly, such as lattice constants and phase transition temperature. Moreover, the physical properties are changed significantly by the stoichiometry and crystallization [8,9]. In general, poly crystal sample has less defect than single crystal prepared by floating zone melting method. The crystal defects can reduce the band gap. Therefore, YbFe_2O_4 poly crystal can have larger band gap than LuFe_2O_4 single crystal.

More detail investigation is required to clarify the mechanism of this abnormal electric conductivity of YbFe_2O_4 under light. The measurement with thin film seems to be useful, considering high light absorption of this material. Nonetheless, the important thing is that the charge ordered material YbFe_2O_4 shows exponential increase of electric conductivity under Ar laser irradiation. If the electric carrier increase exponentially under the

light, novel devices can be developed, such as high efficiency solar cell and sensitive light sensor.

4 CONCLUSION

We measured electric conductivity of YbFe_2O_4 poly crystal under Ar and He-Ne lasers. Most of the energy of He-Ne laser was used to heat the sample. The electric conductivity increases exponentially with increase of Ar laser intensity, despite that electric conductivity increases proportionately to light intensity in general semiconductor. This phenomenon is induced by something other than heating effect and general carrier excitation. The melt of the charge order is likely to have relation to the mechanism.

5 REFERENCES

- [1] N. Kimizuka, E. Takayama-Muromachi and K. Siratori, *Handbook on the Physics and Chemistry of Rare Earths 13* ed K. A. Gschneidner Jr and L. Eyring (North-holland: Elsevier) pp 283-384 (1990).
- [2] N. Ikeda, H. Ohsumi, K. Ohwada, K. Ishii, T. Inami, K. Kakurai, Y. Murakami, K. Yoshii, S. Mori, Y. Horibe, and H. Kito, *Nature (London)*, **436**, 1136 (2005).
- [3] T. Nagata, P.-E. Janolin, M. Fukunaga, B. Roman, K. Fujiwara, H. Kimura, J.-M. Kiat, and N. Ikeda, *Appl. Phys. Lett.* **110**, 052901 (2017).
- [4] A. Enomura, S. Asai, Y. Ishiwata, T. Inabe, Y. Sakai, N. Tsuda, M. Tanaka, and K. Siratori, *J. Phys. Soc. Jpn.*, **52**, 4286-4290 (1983).
- [5] H. Itoh, K. Itoh, K. Anjyo, H. Nakaya, H. Akahama, D. Ohishi, S. Saito, T. Kambe, S. Ishihara, N. Ikeda, and S. Iwai, *Journal of Luminescence*, **133**, 149-151 (2013).
- [6] T. Nagata, Y. Fukada, M. Kawai, J. Kano, T. Kambe, E. Dudzik, R. Feyerherm, P. E. Janolin, J. M. Kiat and N. Ikeda, *Ferroelectrics* **442**, 45-49 (2013).
- [7] S. M. Sze and Kwok K. Ng, *Physics of Semiconductor Devices 3* ed Wiley & Sons, Inc., Hoboken, New Jersey, pp 667-671 (2007).
- [8] T. Michiuchi, Y. Yokota, T. Komatsu, H. Hayakawa, T. Kuroda, D. Maeda, Y. Matsuo, S. Mori, K. Yoshii, N. Hanasaki, T. Kambe, and N. Ikeda, *Ferroelectrics* **378**, 175 (2009).
- [9] K. Fujiwara, T. Karasudani, M. Fukunaga, H. Kobayashi, J. Kano, P.-E. Janolin, J.-M. Kiat, Y. Nogami, R. Kondo, N. Ikeda, *Ferroelectrics* **512**, 85 (2017).

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