Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 956-958

Electrical Properties of Ferroelectric Gate HEMT Structures

Shun-ichiro OHMI, Makoto YOSHIHARA, Takeo OKAMOTO,
Eisuke TOKUMITSU and Hiroshi ISHIWARA

*Precision & Intelligence Laboratory, Tokyo Institute of Technology,
4259 Nagatsuta, Midori-ku, Yokohama 226, Japan*

Electrical properties of ferroelectric $BaMgF_4$ films grown on AlGaAs/GaAs(100) high-electron-mobility transistor (HEMT) structures have been investigated. It is shown that ferroelectric hysteresis measurements for mainly (140)-oriented $BaMgF_4$ films yield spontaneous polarization and coercive field values of almost 1.2 $\mu C/cm^2$ and 230 kV/cm, respectively. In addition, the threshold shift (memory window) as large as 2.7 V is demonstrated from the capacitance-voltage (*C-V*) hysteresis measurements for a $BaMgF_4$(140)/HEMT structure.

1. INTRODUCTION

Ferroelectric gate high-electron-mobility transistor (HEMT) structures have been attracting interest for future device applications such as high-speed adaptive learning devices.[1,2] It is expected in this structure that two-dimensional electron gas (2DEG) can be controlled by polarization of the ferroelectric gate insulator. So far, several ferroelectrics/semiconductor structures have been fabricated using oxide ferroelectrics.[3-7] However, they are unsuitable for the growth on HEMT structures because of the surface oxidation of compound semiconductors. Therefore, in this study, we use $BaMgF_4$ as a ferroelectric material on the HEMT structures. The relative permittivity of $BaMgF_4$ is nearly equal to that of most semiconductors. This asset makes $BaMgF_4$ promising for such device applications.

$BaMgF_4$ is an orthorhombic crystal with lattice constants of a = 0.581 nm, b = 1.451 nm and c = 0.431 nm. The crystal exhibits spontaneous polarization P_s along the a-axis of about 7.7 $\mu C/cm^2$.[2,8,9] Thus, in this application, it is necessary to obtain an a-axis-oriented $BaMgF_4$ film. Recent results of our experiments show that (140)-oriented $BaMgF_4$ films, although not a single crystal, are obtained on the HEMT structure when the growth temperature is higher than 500°C.[1] Since the a-axis of (140)-oriented $BaMgF_4$ film is 32°-off from the substrate surface, the film should have 53% (about 4.0 $\mu C/cm^2$) of the bulk P_s value.

In this paper, we investigate the electrical properties of the $BaMgF_4$/AlGaAs/GaAs(100) structures by polarization vs. electric field (*P-E*) hysteresis measurements and capacitance-voltage (*C-V*) measurements.

2. EXPERIMENTAL

Figure 1 illustrates the structure of samples studied in this work. The $BaMgF_4$/AlGaAs/GaAs(100) structures were grown using a molecular beam epitaxy (MBE) system with two growth chambers: one is for the growth of AlGaAs and GaAs films and the other is for the growth of $BaMgF_4$ films. N-type GaAs(100) substrates were chemically cleaned and loaded into the MBE system. Prior to the growth of AlGaAs/GaAs films, the substrates were thermally cleaned at 610°C for 10 min. After the thermal cleaning, the modulation-doped $Al_{0.3}Ga_{0.7}As$/GaAs heterostructures with high-mobility 2DEGs were grown at 600°C in the AlGaAs/GaAs growth chamber. The structures consisted of a 500 nm undoped GaAs buffer layer on an n-type GaAs(100) substrate, a 15 nm undoped AlGaAs spacer layer, and a 25 nm Si-doped AlGaAs carrier-supplying layer (7.0×10^{17} cm^{-3}). A typical Hall mobility of 2DEG was 7900 $cm^2/(V{\cdot}s)$ at room temperature and 104000 $cm^2/(V{\cdot}s)$ at 30K. Next, the wafer was transferred to the $BaMgF_4$ deposition chamber without exposure to air. $BaMgF_4$ films (200 nm) were then grown on the HEMT structure at growth temperatures from 450 to 600°C by evaporating the $BaMgF_4$ source.[1]

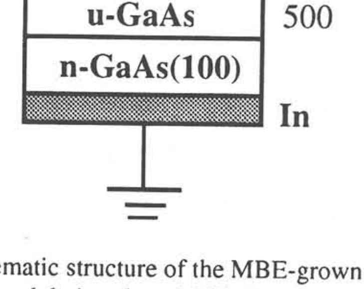

Fig. 1. The schematic structure of the MBE-grown $BaMgF_4$ film on modulation-doped AlGaAs/GaAs(100) heterostructure.

For electrical measurements, aluminum (Al) electrodes of 200 μm in diameter were formed on the film surface and indium (In) electrodes for ohmic contacts were formed on the backside of the substrate during the MBE growth. The *P-E* hysteresis measurements were performed using a Sawyer-Tower bridge and the *C-V* characteristics of the structures were measured with an LCR meter. Both measurements were performed at room temperature.[10]

3. RESULTS AND DISCUSSION

3.1 P-E Hysteresis Measurements

First, we investigated the ferroelectric properties of the (140)-oriented $BaMgF_4$ films. The $BaMgF_4$ films grown directly on the GaAs substrates were amorphous at the growth temperature of 450°C, whereas mainly (140)-oriented films were obtained on GaAs substrates and also on the HEMT structures at growth temperatures of 500–600°C.[1]

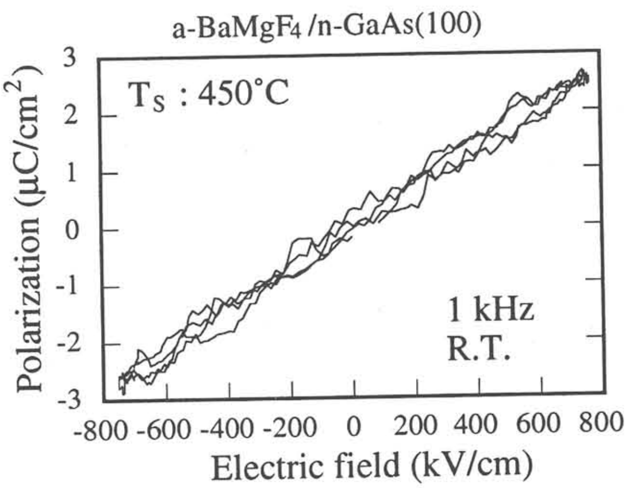

Fig. 2. The typical *P-E* hysteresis plot of the amorphous $BaMgF_4$ film grown on the n-type GaAs(100) substrate at 450°C.

Figure 2 shows the result of 1 kHz *P-E* hysteresis measurements for the amorphous $BaMgF_4$ film grown on n-type GaAs(100) substrate at 450°C. It is found that the amorphous film does not show the ferroelectric characteristics as shown in Fig. 2. On the other hand, the (140)-oriented film shows a clear ferroelectric hysteresis loop as shown in Fig. 3. From this result, it can be said that the (140)-oriented $BaMgF_4$ film has the ferroelectric properties along the growth direction. The hysteresis loop is off-centered, probably because of the effect of the dissimilar electrodes. The remanent polarization P_r of this film is found to be about 1.2 μC/cm^2. The coercive field of this film is about 230 kV/cm. The P_r value is significantly less than the expected value of 4.0 μC/cm^2, partly because the crystallinity of the film was not good compared with the bulk materials.

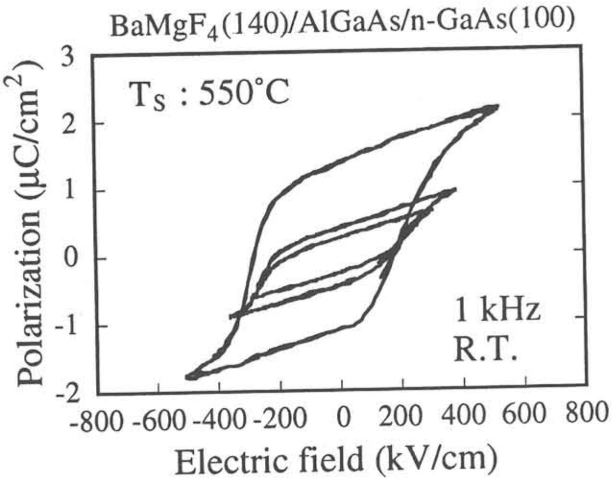

Fig. 3. The typical *P-E* hysteresis plot of the (140)-oriented $BaMgF_4$ film grown on the undoped-AlGaAs/n-GaAs(100) substrate at 550°C.

3.2 C-V Measurements

For device applications, it is important to investigate from the *C-V* characteristics if the threshold voltage can be really controlled by the ferroelectric properties of the (140)-oriented $BaMgF_4$ films.

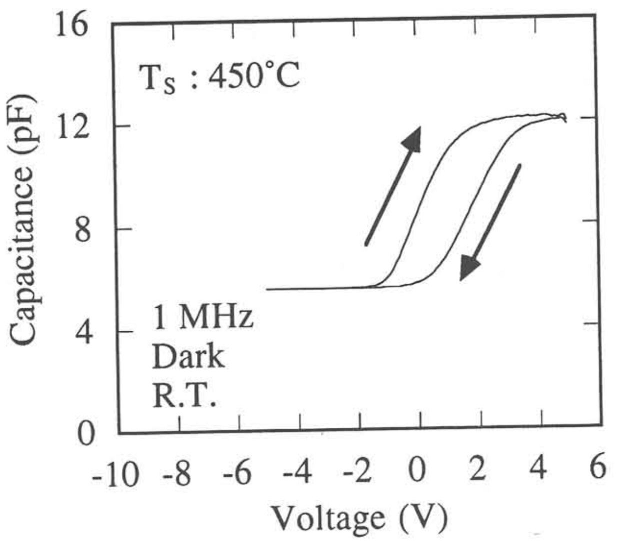

Fig. 4. The *C-V* characteristic of $BaMgF_4$/HEMT structure with the (011)-oriented $BaMgF_4$ film. The $BaMgF_4$ film was grown at 450°C.

Figure 4 shows the typical 1 MHz *C-V* characteristic for the structure shown in Fig. 1, which the growth temperature of the $BaMgF_4$ film was 450°C. When the $BaMgF_4$ films are grown at 450°C, (011)-oriented films are obtained on the HEMT structures whose *a*-axis is parallel to the surface of the sample. It is found that the *C-V* curve shows hysteresis loops. However, for a (011)-oriented $BaMgF_4$ film, the hysteresis loop was clockwise as indicated by arrows in Fig. 4. This result was probably caused by the charge injection to the traps in the $BaMgF_4$ film near the $BaMgF_4$/AlGaAs interface. On the other hand, although the characteristics are sensitive to light illumination, a counterclockwise hysteresis was obtained for the (140)-oriented film grown at 600°C as shown in Fig. 5. The threshold shift (memory window) was about 2.7 V under the bias condition. This phenomenon is probably caused by the remanent polarization of (140)-oriented $BaMgF_4$ films.

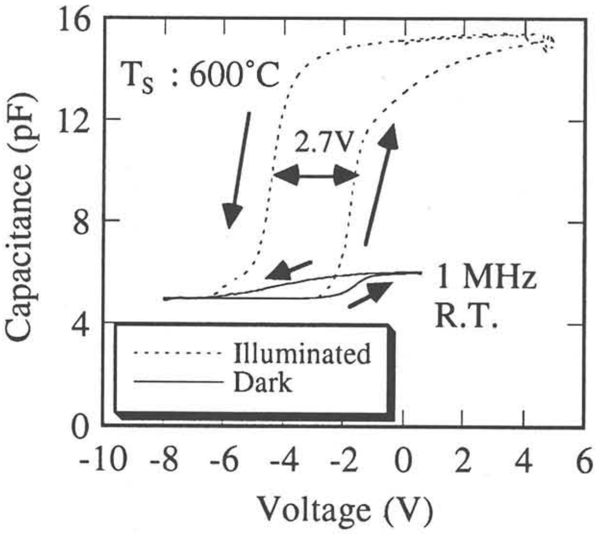

Fig. 5. The *C-V* characteristic of $BaMgF_4$/HEMT structure with the (140)-oriented $BaMgF_4$ film. The $BaMgF_4$ film was grown at 600°C.

4. CONCLUSIONS

We have investigted electrical properties of $BaMgF_4$/AlGaAs/GaAs(100) structures and demonstrated a counterclockwise hysteresis for the structure with (140)-oriented $BaMgF_4$ films. This suggests to the ferroelectric nature of $BaMgF_4$ films. Since we have already reported that the mobility of 2DEG at the AlGaAs/GaAs interface is not seriously degraded when the growth temperature is lower than 600°C,[2)] we can conclude from the results in this paper that (140)-oriented $BaMgF_4$ films formed in the temperature range from 500°C to 600°C are promising for realizing the future functional devices using ferroelectrics/HEMT structures.

ACKNOWLEDGMENTS

This work was partially supported by a Grant-in-Aid for Scientific Research on Priority Areas (No.07248105) and by a Grant-in-Aid for Scientific Research (B) (No.07455134) from the Ministry of Education, Science and Culture. One of authors (S. Ohmi) is also thankful to the support by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists.

REFERENCES

1) S.Ohmi, E.Tokumitsu, and H.Ishiwara : J. Cryst. Growth in press.
2) S.Ohmi, E.Tokumitsu, and H.Ishiwara : Jpn. J. Appl. Phys. Lett. **34** (1995) L603
3) S.Y. Wu: IEEE Trans. Electron Devices **ED-21** (1974) 499.
4) S.Y. Wu: Ferroelectrics **11** (1976) 379.
5) K. Sugibuchi, Y. Kurogi and N. Endo: J. Appl. Phys. **40** (1975) 2871.
6) Y. Higuma, Y. Matsui, M. Okuyama, T. Nakagawa and Y. Hamakawa: J. Appl. Phys. **17** (1977) 209.
7) T.A. Rost, H. Lin and T.A. Rabsom: Appl. Phys. Lett. **59** (1991) 3654.
8) E.T. Keve, S.C. Abrahams and J.L. Berntein: J. Chem. Phys. **51** (1969) 4928.
9) S. Sinharoy, H. Buhay, M.G. Burke, D.R. Lampe and T.M. Pollak: IEEE Trans. Ultrason. Ferroelectr. & Freq. Control **38** (1991) 663.
10) K. Aizawa and H. Ishiwara: Jpn. J. Appl. Phys. **33** (1994) 5178.