Electrical Properties of Metal-Insulator-Semiconductor (MIS) Using Low Temperature Deposition of ZnO as Semiconductor Layer

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***Abstract*- This paper investigates the performance of low temperature zinc oxide (ZnO) film as semiconductor and poly(methyl methacrylate) (PMMA) as insulator layer in metal-insulator-semiconductor (MIS) structure. ZnO films were grown at different temperatures from 40ºC, 60ºC, 80ºC, 100ºC and 120ºC. XRD result revealed that ZnO film grown at 120ºC has (002) crystal structure with better crystallinity compared to the other temperatures. FESEM image show structure transformation of ZnO grain from rice shape to round shape at 120ºC. MIS with ZnO grown at 120ºC give the best electrical properties with current value of 38 x10^{-6} A and conductivity about 278 x 10^{-6} S/cm at 10V, compared to the other temperature. MIS with ZnO grown at 120ºC indicate the highest dielectric constant, *k* with value of 7.7 at 1 KHz and 6.2 at 1 MHz. The best characteristics of MIS obtained from the structure with ZnO grown at 120ºC due to high conductivity, high crytallinity, good surface morphology and high *k* value.**

***Keywords:* ZnO; deposition temperature; MIS; electrical properties; structural properties**

I. INTRODUCTION

Metal-insulator-semiconductor structure is formed from a layer of metal, insulator, and semiconductor material. It is similar to MOS structure except that the insulator layer made of different material which is polymer [1] instead of oxide. MIS structure is the simplest structure to investigate the behaviour and compatibility between the semiconductor and insulator layer before fabricating field effect transistor (FET) [2, 3]. The interface between isulator-semiconductor layer will determine the device performance [3]. Therefore, it is necessary to ensure the proper selection of materials to formed both layers.

There are several semiconductor material such as ZnO [4], galium arsenide (GaAs) [5] and silicon (Si) [6] being used as semiconductor layer in MIS structure. ZnO is chosen because of its good semiconducting properties. ZnO is an n-type semiconductor material, it has high electron mobility of 0.2 to 31 cm^2/V and a wide band gap of ~ 3.2 eV [7, 8]. Other advantage of ZnO is the semiconductor properties, it is maintained even when deposited at low temperature [9, 10]. Radio frequency (RF) magnetron sputtering technique was used to deposit the ZnO layer because it can produce a uniform and good quality of ZnO film [11, 12]. In this work, low temperature deposition of ZnO were used to form ZnO semiconductor layer due to the use of polymer material as insulation layer. This polymer material can only withstand a maximum temperature of 160ºC. Poly (methyl methacrylate) (PMMA) has been used as insulator layer in organic devices such as organic field effect transistor (OFET). This is because PMMA has good dielectric properties such as *k* value of 2.6 measured at 1 MHz [13].

The purpose of this work is to investigate the electrical properties of MIS using low deposition temperature of ZnO film as semiconductor layer and PMMA as insulator layer in MIS structure. The effect of different deposition temperature (40ºC, 60ºC, 80ºC, 100ºC and 120ºC) of the ZnO film in MIS were characterized using current-voltage and impedance measurement. X-ray diffraction (XRD) were measured to determine the characteristics of ZnO grown, meanwhile Raman was used to determine the PMMA/ZnO film behaviour. The morphology of ZnO and PMMA/ZnO film were investigated using FESEM.

II. METHODOLOGY

Figure 1 shows the flowchart of experimental setup. Glass slides were cleaned using acetone, methanol and de-ionized (D.I) water in ultrasonicator; each for 10 minutes. The glass slides were then dried using nitrogen (N_2). Titanum (Ti) and aluminum (Al) were deposited to form the bottom contact. Both layer thickness is 60nm and 40nm respectively. ZnO was grown using RF magnetron sputtering to form semiconductor layer. ZnO with high purity (99.999%) was used as the target. The pressure chamber was set at 5 x10^{-4} Pa and the argon gas flow rate set to 45 sscm. The pressure of the chamber was maintained at 5 x10^{-3} Torr. The deposition temperature were varied at 40ºC, 60ºC, 80ºC, 100ºC and 120ºC. The RF power was set to 200W for 1 hour deposition. The substrates were pre-sputtered for 10 seconds before the deposition. PMMA layer acting as insulator layer were deposited using spin-coating technique. PMMA solution was prepared by dissolving 0.6g of PMMA (SIGMA Aldrich) with molecular weight of 120,000 in 10ml tetrahydrofuran (THF) (ChemAr). The solution was sonicated for 30 minutes at 50ºC before stirred for 24 hours using magnetic stirrer. The rotation speed was fixed at 3000 rpm for 60 seconds. Top contact was deposited using Al with thickness of 100nm.

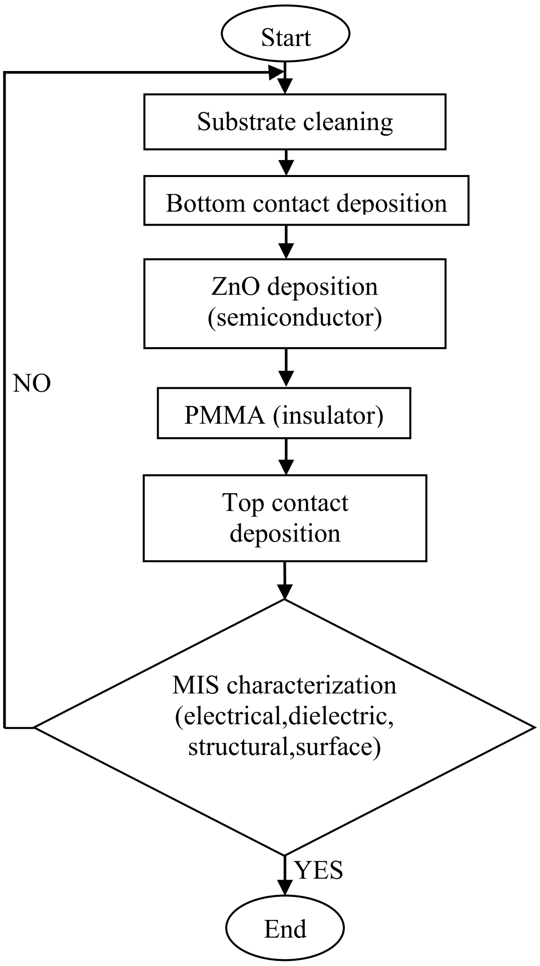

Figure 1. Experimental setup

The MIS were characterized using the structure as shown in Fig. 2. The electrical properties were measured using current-voltage (I-V) measurement (Keithley) and impedance spectroscopy (Solatron 1260). The structural properties and morphology were investigated using X-ray diffraction (XRD), Raman spectrometer and field emission scanning electron microscopy (FESEM) (JEOL JSM 7600F).

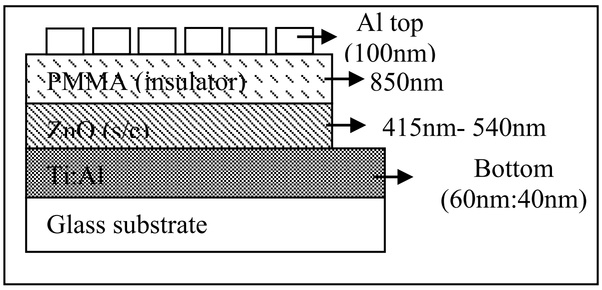

Figure 2. MIS structure

III. RESULT AND DISCUSSION

A. Electrical Properties

Figure 3 show the I-V curve of ZnO film for applied voltage from -10V to 10V. Result obtained show ohmic contact behavior. Highest current value of 20 x10^{-6} A obtained from ZnO film deposited at 120ºC, suggesting higher conductivity with increasing deposition temperature. Figure 4 show the resistivity and conductivity of ZnO film at different deposition temperature. The resistivity and conductivity of the film were calculated using Eq. 1 and Eq. 2 below.

$$\rho = \left(\frac{V}{I}\right)\left(\frac{wt}{x}\right) \quad (1)$$

$$\sigma = \left(\frac{1}{\rho}\right) \quad (2)$$

where ρ is the resistivity, V is the voltage, I is the current, w is the width, t is the thickness, x is the distance between electrodes, and σ is the conductivity. Graph show that resistivity decreased, while conductivity increased with increasing deposition temperature. The resistivity obtained for ZnO film is around ~ 10^3 Ωcm, while the conductivity is around ~ 10^{-3} S/cm. ZnO film deposited at 120ºC show the highest conductivity compared to the other deposition temperature.

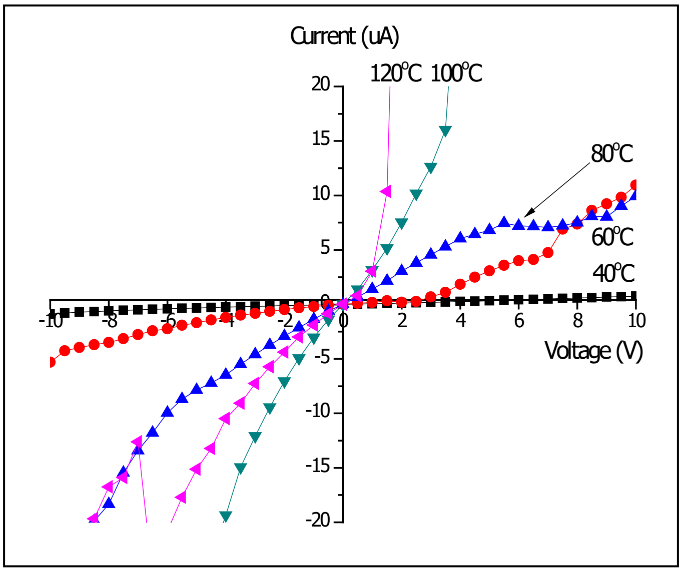

Figure 3. I-V for ZnO film at different deposition temperature

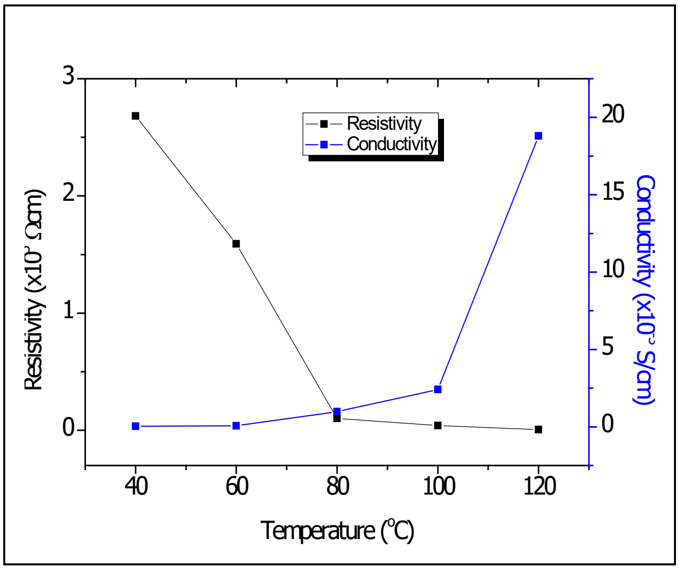

Figure 4. Resistivity and conductivity versus temperature for ZnO film

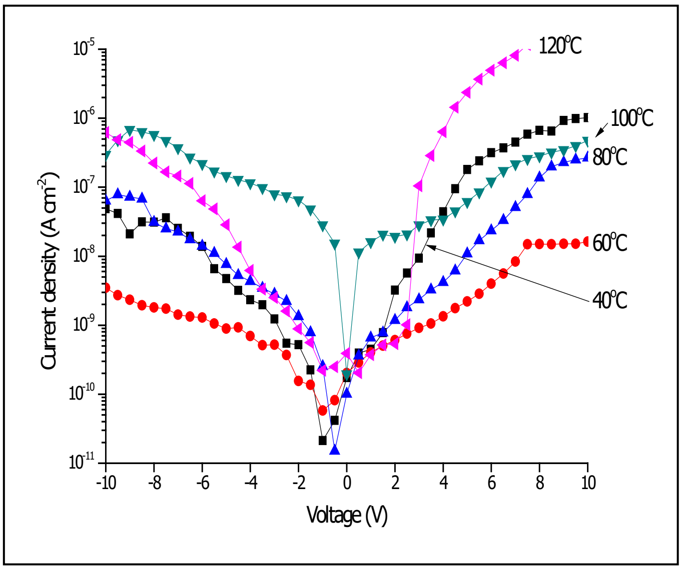

Figure 6. Leakage current density versus temperature for MIS structure

Figure 5 show I-V curve of MIS structure at different deposition temperature. Curve obtained revealed rectifying characteristic due to the difference in work function between Al, PMMA and ZnO. Figure 6 show leakage current density of MIS structure at different deposition temperature. Leakage current density obtained increased from 10^{-11} A/cm^2 to 10^{-5} A/cm^2. Increase in leakage current density was due to the porosity of PMMA layer.

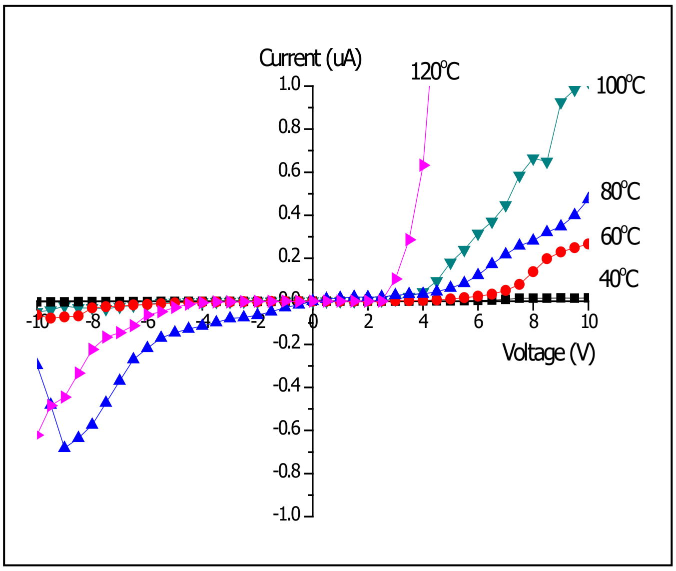

Figure 5. I-V for MIS structure at different deposition temperature

B. Dielectric Properties

Dielectric constant, k of MIS structure at different deposition temperature shown in Fig. 7. Value of k for PMMA reported by other researchers is between 6 to 7 at 1 kHz [14, 15] and 2.6 at 1 MHz [1, 13]. Meanwhile for ZnO, k is ~ 40 at 1 kHz [16] and between 4 to 7 at 1 MHz [16, 17]. Value of k obtained for MIS is between 5.3 to 7.7 at 1 kHz and 4 to 6.2 at 1 MHz. The k value increased with increasing deposition temperature due to the decreasing size of ZnO nanoparticles as deposition temperature was increased. The particle per unit volume become large, thus high dipole moment per unit volume is produced [18].

Capacitance is an important characteristic to determine the behaviour of MIS devices. Value of capacitance indicated how much charge can be accumulated in the device. Capacitance of the MIS can be calculated using following Eq. 3 below.

$$C = \left(\frac{\varepsilon_o \varepsilon_r A}{d}\right) \quad (3)$$

where C is the capacitance, ε_o is permittivity of vacuum, ε_r is the relative permittivity also known as dielectric constant, A is the area, and d is the thickness of dielectric layer. Figure 8 show the capacitance value of MIS versus ZnO deposition temperature measured at 1 kHz and 1 MHz. The capacitance value for MIS with different ZnO deposition temperature observed at 1 kHz is between 2 x10^{-10} F to 3.5 x10^{-10} F, while at 1 MHz is between 3 x10^{-10} F to 4.5 x 10^{-10} F. MIS structure with ZnO deposit at 120°C gives the highest capacitance compared to other temperature indicating higher amount of accumulated charges.

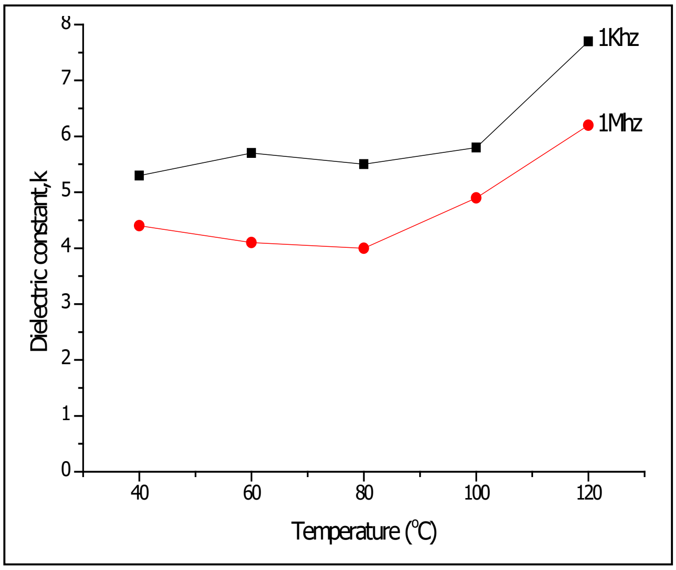

Figure 7. Dielectric constant versus temperature for MIS at 1 kHz and 1 MHz

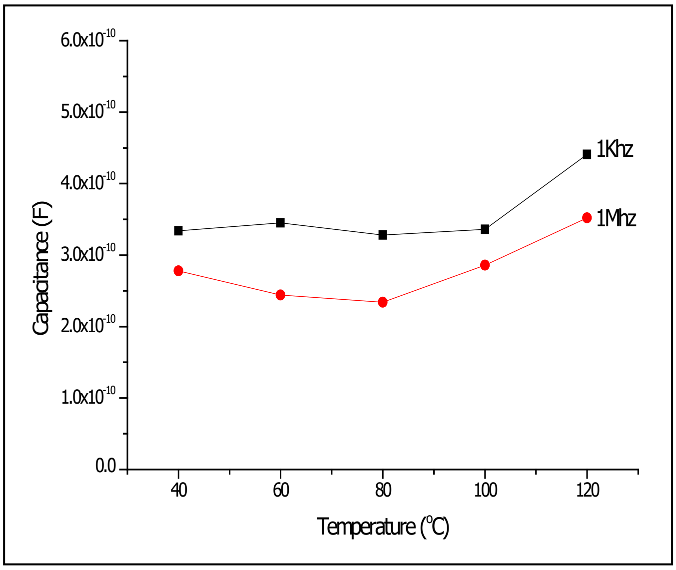

Figure 8. Capacitance versus temperature of MIS at 1 kHz and 1 MHz

C. Structural Properties

Figure 9 show the XRD pattern of ZnO film at different deposition temperature. The structure was identified to be polycrystalline with wurtzite structure. All low temperature ZnO film show the strong common ZnO peaks that being reported by other researchers. Strong peak at 34.7° was observed, corresponding to ZnO (002) peaks of ZnO. Meanwhile, ZnO (101) peak was oberved at 36.7°. Strong ZnO (002) peak compared to neighboring ZnO (101) suggested the preferrential growth orientation along c-axis perpendicular to substrate surface. Shinho Cho *et al.* characterize the ZnO film at different temperature and also obtained a similar characteristic [7]. The crystallinity of ZnO film also increased with the increasing deposition temperature [7, 10]. Result obtained from XRD suggest that crytallinity of ZnO film still good even when deposited at low temperature.

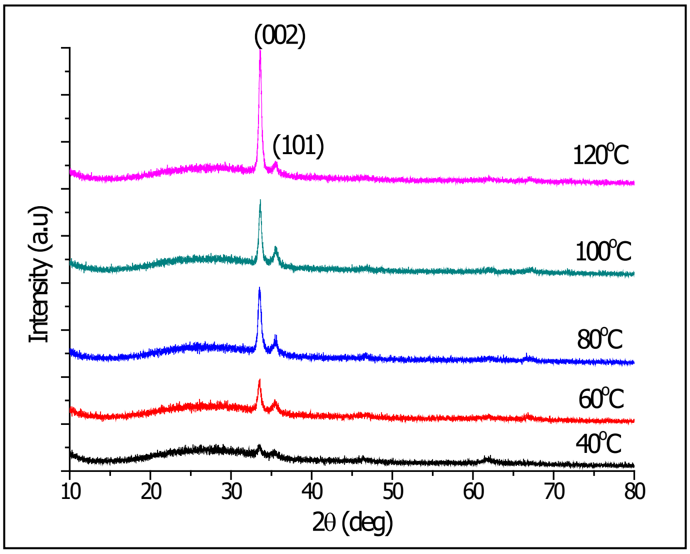

Figure 9. XRD pattern of ZnO film at different deposition temperature

Figure 10 show Raman spectra for PMMA/ZnO film deposited at different temperature. In the spectrum it can be seen that, three peaks observed; A_1 (Lo) at 572 cm^{-1} which belongs to ZnO [19], $2E_1$ (Lo) at 1099 cm^{-1} belongs to PMMA/ZnO, and 2947 cm-1 which belongs to PMMA [20]. Presence of PMMA on top of ZnO revealed that there is an interaction between ZnO and PMMA film and are further evidence of good band allignment between ZnO and PMMA [20].

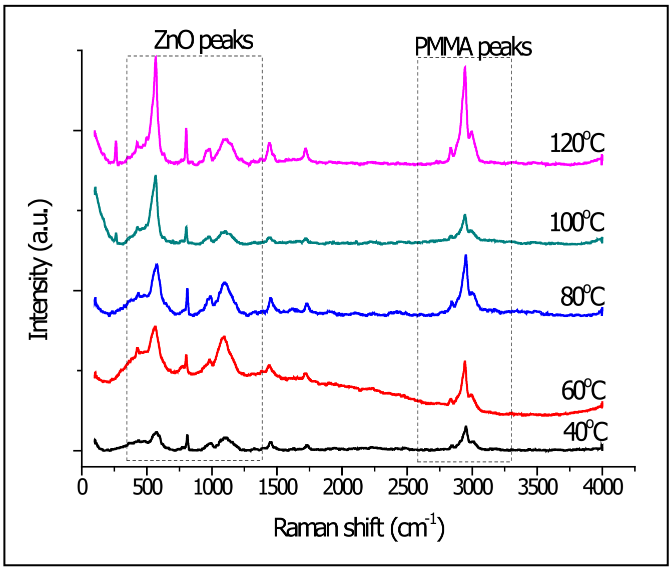

Figure 10. Raman spectra for PMMA/ZnO film at different deposition temperature

D. Surface Morphology

Figure 11 show FESEM image for ZnO film at different deposition temperature. Image revealed the transformation of ZnO nanoparticles from rice shape to round shape grain at 120ºC. The size of ZnO grain also decreased with increasing deposition temperature. Result suggest that ZnO film deposited at 120ºC give better surface morphology compared to the other temperature. The electron migration in MIS improved due to changes in size and shape of ZnO nanoparticles.

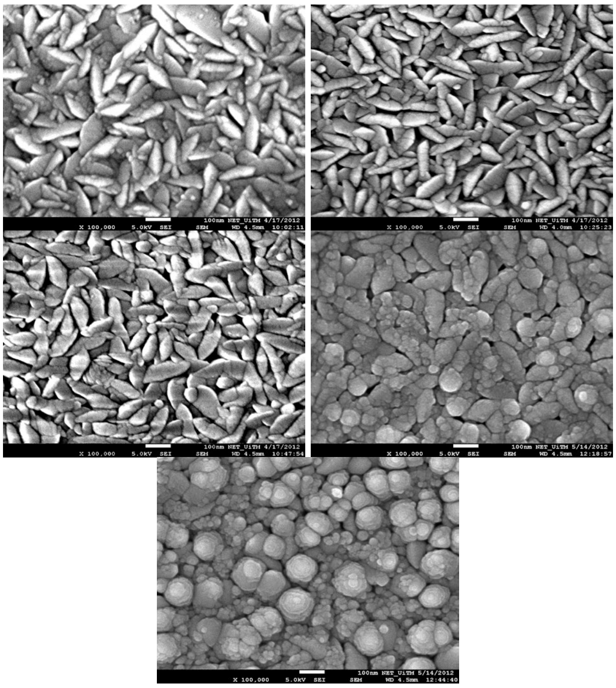

Figure 11. FESEM image of ZnO film at different deposition temperature

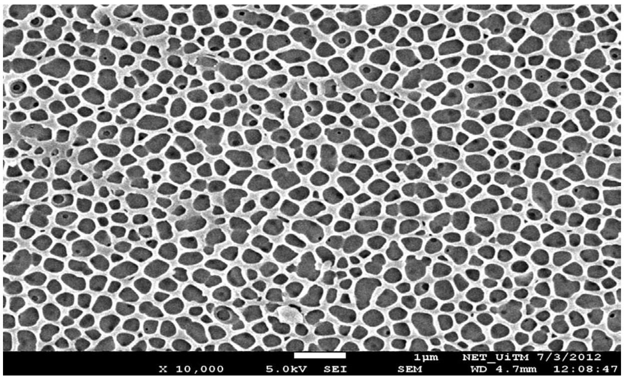

Figure 12. FESEM image of PMMA/ZnO film at 120ºC

FESEM image of PMMA layer grown on top of ZnO layer with deposition temperature of 120ºC is shown in Fig. 12. Porous surface of PMMA layer can be observed in this image with distance between pores about 60 nm apart. The porosity of PMMA layer is due to the THF solvent used in the PMMA solution. The THF vaporised very fast when annealed at 120ºC and produced the porous PMMA surface. The porous surface only produced at the surface of PMMA layer.

TABLE 1. Surface properties of film at different deposition temperature

Substrate temperature (ºC)	ZnO film thickness (nm)	Average roughness ZnO film (nm)	Average roughness of PMMA (nm)
40	415.1	0.952	1.972
60	474.9	1.140	2.085
80	495.5	1.360	2.335
100	520.0	2.696	5.484
120	540.0	5.326	5.750

IV. CONCLUSION

The electrical properties of MIS using low deposition temperature of ZnO as semiconductor layer have been successfully investigated. Properties of low temperature ZnO film indicate that film deposited at 120ºC gives the best electrical, structural and morphology properties to be used as a semiconductor layer. The conductivity of ZnO deposited at 120ºC is 18.6 $\times 10^{-3}$ S/cm. This value are less than being reported by other researcher which is 8 $\times 10^{-2}$ S/cm at 200ºC [11]. Raman studies proved the presence of ZnO and PMMA, as well as interaction between ZnO and PMMA in MIS structure.

Value of k for PMMA/ZnO film increased with increasing deposition temperature from 5.3 to 7.7 at 1 kHz and 4 to 6.2 at 1 MHz. With increasing deposition temperature, the conductivity and leakage current density of MIS structure increase significantly. MIS device with ZnO deposited at 120ºC reveal the conductivity of 278 $\times 10^{-6}$ S/cm. Result obtained suggest that deposition temperature improve the electrical performance of MIS structure as reported by other researcher [21].

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