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The heat performance study of nanocrystal diamond film used in a thin film device

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Abstract

We studied the heat performance of nanocrystal diamond film and a silicon dioxide film by measuring the temperature of Si layer covered by these insulating films. We applied the voltage to the Si layer to increase temperature. The temperature of the Si varies with the thickness of the insulating film made from silicon dioxide. To replace the insulating film of silicon dioxide by a nanocrystal diamond makes better cooling. The results showed the temperature of the Si covered with the silicon dioxide film was 100 °C while the temperature of Si covered with the nanocrystal diamond film was 80 °C at the same applied power despite the nanocrystal diamond film is thicker than the silicon dioxide by 100 nm.

1. Introduction

Power consumption of power semiconductor (Regulator) devices used in the information and communication apparatus have been raising. Self-heating of the power IC should be reduced for the future apparatus, which will consume more power. The silicon-on-insulator (SOI) technology is currently based on the system, which silicon dioxide (SiO_2) is a buried oxide (BOX) layer. Most of its properties are good, though thermal conductivity is poor. To replace SiO_2 with diamond is possible to reduce the temperature because the thermal conductivity of diamond is large. The thermal conductivity of SiO_2 is 1.4 $W.m^{-1}.K^{-1}$ whereas diamond depends on its crystallinity as follows; 20, 2000 $W.m^{-1}.K^{-1}$ is a nanocrystal and single-crystal diamond respectively. The impact of nanocrystal diamond is shown by simulation as a BOX layer in silicon-on-diamond (SOD) structure that it can reduce temperature 40K compare with SOI. In that value, the breakdown voltage of power MOSFET increases 4-5 V and on-resistance reduces to 5% approximately. Furthermore, in case of IC LSI, an insulating layer between the interconnecting wire is made from SiO_2. Obviously, the heat generated during device activity is proportional to the number of layers. So that if the nanocrystal diamond film is placed in the insulating layer instead of SiO_2, the device temperature will decrease and the performance of the system will increase same as above reasons.

We investigate the relationship between the applied power and the temperature of thin film Si covered with the nanocrystal diamond and a conventional use SiO_2. The thin film Si is act as a heater and a thermometer.

2. Design of Si thermometer

The Si thermometer is made from the theory of resistance of semiconductor which dependent on dimension and resistivity. The resistivity dependent on electron mobility and amount of carrier that both of two parameters varie with temperature as follows:

$$R = \rho \frac{L}{W \times t} \quad (1)$$

R is resistance (Ω), ρ is resistivity (Ω·cm) and L, w, t are dimension of resistance body (cm)

$$\rho = \frac{1}{qn(T)\mu_n(T)} \quad (2)$$

q is elementary charge, $\mu_n(T)$ is electron mobility ($cm^2/V\cdot s$) and $n(T)$ is density of free electron, both of $n(T)$ and $\mu_n(T)$ are dependent on temperature but density of free electron at any temperature is dependent on two quantities as follows:

$$n(T) = n_i(T) + N_D \quad (3)$$

$n_i(T)$ is intrinsic concentration (cm^{-3}) and N_D is donor-impurity density (cm^{-3}), which $N_D >> n_i(T)$ that means $n(T) \cong N_D$. We can reduce all equation from (1), (2) and (3) as new form:

$$R = R(T) = \left(\frac{L}{qN_D Wt} \right) \cdot \frac{1}{\mu_n(T)} \quad (4)$$

Now, equation (4) is shown how to design the Si thermometer, which resistance change depend on temperature.

3. Fabrication of the sample and measurement

From SOI wafer, it was doped with phosphorus as design concentration 1×10^{17} cm^{-3}. After thermal treatment, and so applied a thermal oxidation process to control the thickness of the body to 250 nm thick. Next step, removed SiO_2 by wet etching and removed unwanted area of the Si sample to make the body shape. The connection point made by doping with phosphorous as design concentration to 1×10^{19} cm^{-3} at the both ends of the body. The analysis insulating film, SiO_2 or nanocrystal diamond was deposited on the Si thermometer. The aluminum wire was made up by dry etching, deposited aluminum and etched unwanted aluminum again. The model has shown in Fig 1.

In step of measurement, we set the equipment as shown in Fig. 2 and started to apply power with 1V fixed during measurement with temperature start $T_0 = 30^{o}$C and recorded the resistance R_0. Then applied temperature varies from T_0 to 300^{o}C and recorded R_x, which were respected of its temperature T_x. The resistance ratio R_x/R_0 was calculated and shown in Fig 3. The second measurement, fixed temperature to 30^{o}C during measurement with voltage start = 1V, then applied voltage varies from 1V to 20V and recorded R_y in each. Then, each of R_y was used to calculate the temperature from R_x data and shown in Fig 4.

4. Temperature measurement results

Figure 3, at the temperature more than 150 ^{o} C, the resistance ratio of SiO_2 with 300 nm thick is higher than 500 nm thick that means a thickness had affected to heat transfer rate in the sample. Slow rate heat transfer means the sample was able to keep heat and its resistance would change a little value that a reason why the resistance ratio of thicker film had shown a lower ratio than thinner film. Whereas nanocrystal diamond film with 600 nm thick showed better heat transfer rate than SiO_2 with 500 nm thick, that means nanocrystal diamond was better than SiO_2 in case of heat spread out of the device. When we changed the data to the same power, which showed in Fig. 4 that the temperature of nanocrystal diamond were lower than SiO_2 despite thicker than 100 nm. It was consistent with above reasons.

5. Conclusions

The nanocrystal diamond film act as a good performance insulating film compare with the silicon dioxide. Even though the thickness of nanocrystal diamond film is twice than that of silicon dioxide film, the result temperatures show the same value. That means the nanocrystal diamond film is greater efficiency in cooling off.

Acknowledgments

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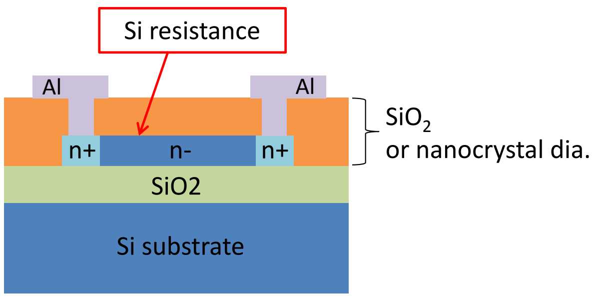

Fig. 1 The model of experimental device.

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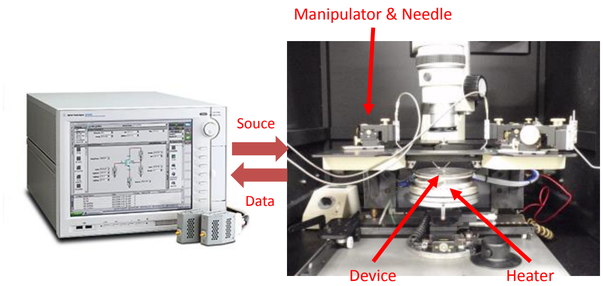

Fig. 2 Instrument and experimental setting.

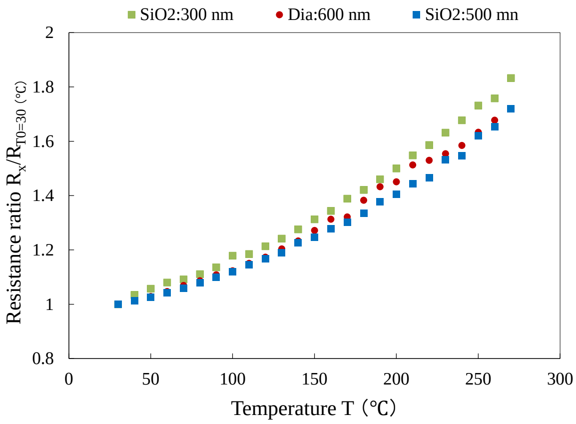

Fig. 3 The graph shows that resistance varies with the temperature of the devices.

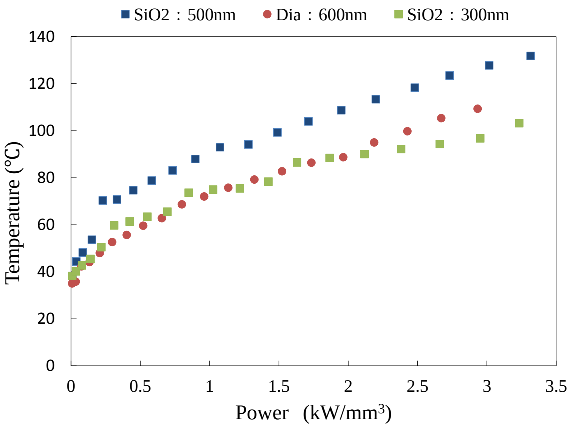

Fig. 4 The graph shows the relationship between power and temperature of the devices.