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Temperature dependent characteristics of diamond MESFET

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1. Introduction

Diamond has the potential to become an important semiconductor for high power and high frequency applications due to its extreme physical and electrical properties, such as a high hole-saturation velocity (>1×10^7cm/s), a high thermal conductivity (20W/cm·K), and a high electric breakdown field (>10MV/cm). High RF performance diamond FET was reported previously by our group (cut-off frequency for current gain: f_T=25GHz; for power gain: f_{max}=81GHz) [1]. In fact, microwave devices have always demanded not only high-frequency operation, but also thermal stability. Thus it is important to understand the device operation mechanism and hydrogen terminated surfaces at elevated temperatures. In this paper, we report the first attempt in measuring temperature dependent RF performance of diamond FETs. In addition, temperature dependent circular transmission line measurements (CTLM) were performed in order to investigate the influence of contact resistance on the device behaviors.

2. Experimental details

A homoepitaxial layer used for the device fabrication was grown on type Ib single crystalline diamond crystals, followed by hydrogen termination to form a p-type conduction near the surface [2]. The surface conductivity of hydrogen terminated diamond has been used as channels in MESFET devices [3]. However, the origin of the surface acceptors and exact energy band near the surface area are still not clear.

Diamond FETs with 0.2 μm gate length and 100 μm gate width were fabricated using electron-beam lithography with self-alignment method on the hydrogen terminated layer. Figure 1 shows the cross-sectional view of a single FET device. The line underneath the surface represents hydrogen-terminated conductive layer.

Purposely-built temperature variable probing stage was used for this study, which enables us to carry out experiments from 20 °C to 100 °C. DC characteristics were measured using HP4192A parameter analyzer and RF characteristics using Agilent Network Analyzer E8364B. CTLM method was used to determine the sheet resistance of the conduction layer and the contact resistance between electrode (Au, 350 nm thick) and hydrogen terminated diamond. The details of this technique can be found elsewhere [4]. All the experiments were carried out in air during the temperature rising.

3. Results and discussion

Figure 2 shows the temperature dependent transconductance (g_m) at drain bias V_{ds}= -8V and gate bias sweeping from +2V to -3.5V. At all the temperatures, g_m increases initially and reaches a maximum value at gate bias V_{gs}= -2V, and decreases after that. With increasing temperature, maximum g_m slightly decreases from 55 mS/mm at 20°C to 48 mS/mm at 100°C. This is a result of the current between drain and source at saturation regions slightly decreasing with increasing temperature. The corresponding resistance between source and drain (R_{ds}) increases with increasing temperatures. From the small-signal equivalent circuit, one can see that R_{ds} is a series of both the contact resistance R_c and the channel resistance R_{ch}. A central issue to be addressed is which part of the resistance dominates R_{ds}.

In order to clarify this, CTLM measurements were performed on the hydrogenated diamond, which has been processed using the same hydrogenation recipe as that for FET device fabrication. Thus the results obtained from the CTLM can be used to analyze the device properties. Figure 3 shows the temperature dependent sheet resistance (R_s) and specific contact resisitivity (ρ_c) using CTLM method from 20°C to 150°C in air. It can be seen that R_s slightly increases with increasing temperature; however, ρ_c increases drastically by two orders of magnitude with increasing temperature. Based on the real dimension of the fabricated device (i.e. gate length 0.2 μm, gate width 100 μm, and spacing between the source and drain 2 μm, area of source or drain electrode 100 μm×50 μm), assuming the sheet resistance is ~5 kΩ and the contact resistivity ~10^{-5} Ω·cm^2 from figure 3, one can calculate that the channel resistance (R_{ch}) between source and drain is ~100Ω, and the contact resistance (R_c) of source or drain is ~0.2 Ω. Thus it can be seen that R_{ch} is most significant in determining the transconductance because of three orders-of magnitudes higher than R_c.

The slightly increase of R_s with increasing temperature may be attributed to the fact that hydrogen-terminated surface conductivities are weakly temperature dependent showing activation energies between 3 and 20 meV [5]. The increase of ρ_c can be explained as the Au electrode degradation and/or the change of adsorbates underneath the electrodes. Since R_{ch} plays a dominant role in determining the device behaviors, it is expected that the current gain is weakly temperature dependent as well.

Figure 4 shows the temperature dependent current gain versus frequency for the FET device at different temperatures. The cut-off frequencies (f_T) slightly decrease from 9 GHz at 20°C to 8 GHz at 100°C. Generally f_T is approximately expressed by the following equation:

$$f_T = \frac{g_m}{2\pi C_{gs}} \tag{1}$$

where C_{gs} is gate-source capacitance. Assuming the temperature influence on C_{gs} can be ignored, from Eq. (1) we may derive that:

$$\Delta g_m / g_m \approx \Delta f_T / f_T \tag{2}$$

This means that the relative change for g_m with temperature is approximately the relative change for f_T with temperature. From figures 2 and 4, one can estimate that g_m decreases by 12.7% from 20°C to 100°C, and f_T decreases by 11.1%. This is in good agreement with Eq. (2). The slight difference between $\Delta g_m/g_m$ and $\Delta f_T/f_T$ may be caused by following factors: (1) system error during the measurements; (2) C_{gs} may also show weakly temperature dependent and make a small contribution.

4. Conclusions

This paper has reported the initial studies on temperature dependent DC and RF characteristic of Diamond FETs. It is found that the transconductance decreases by 12.7% from 20°C to 100°C, while cut-off frequency decreases by 11.1% from 20°C to 100°C. CTLM results have shown that the electrode contact resistance has a negligible effect on the device behavior due to its small contribution compared with the sheet resistance. The hydrogenated conductive channel plays a critical role in determining the device behaviors at high frequencies and elevated temperatures. In general, the device under-study is believed to be thermally stable up to 100°C as it does not deteriorate at higher temperatures with a cut-off frequency maintained around 8~9 GHz.

References

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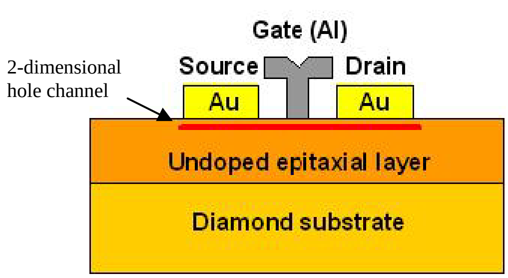

Figure 1. Cross-sectional configuration of diamond MESFET.

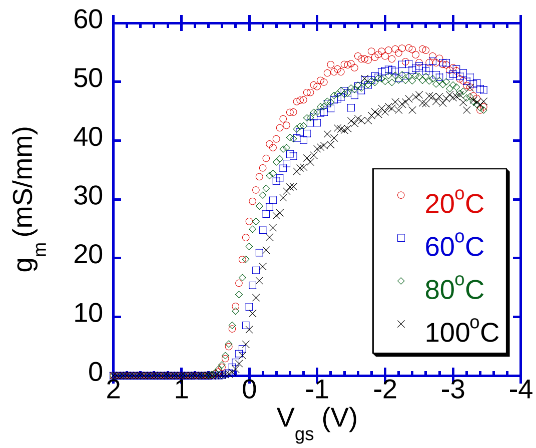

Figure 2. Temperature dependent transconductance at V_{ds}= -8V.

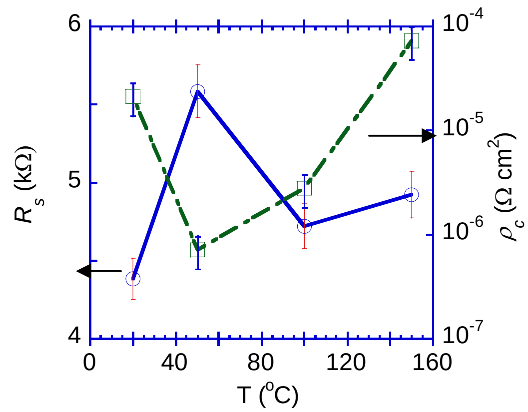

Figure 3. Temperature dependent sheet resistance (R_s) and specific contact resistivity(ρ_c) using CTLM method.

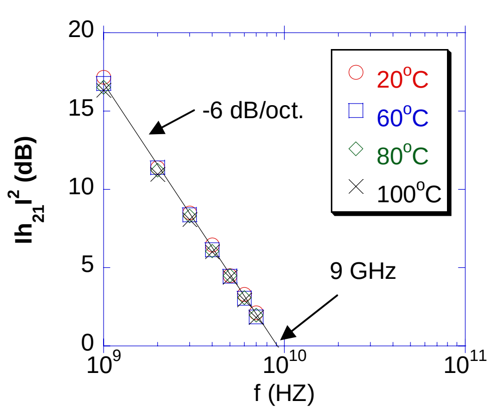

Figure 4. Temperature dependent current gain versus frequency for diamond MESFET (gate length 0.2 μm, gate width 100 μm) at V_{ds}=-10V, V_{gs}=-1V.