# Stability of H-Terminated Diamond MOSFETs with $V_2O_5/Al_2O_3$ as Gate Insulator

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***Abstract*— The effectiveness and long-term stability of surface transfer doping of H-terminated diamond induced by a very thin $V_2O_5/Al_2O_3$ double layer were deeply investigated. Experimental results demonstrate that the deposition of a 5 nm $Al_2O_3$ layer does not alter the transfer doping properties of the $V_2O_5$/H-terminated diamond interface and remarkably improves stability over time of the Hall parameters.**

**H-diamond MOSFETs were fabricated by using $V_2O_5/Al_2O_3$ as gate insulator and characterized in terms of DC characteristics. The devices showed a saturation drain current density of about 220 mA/mm. Repeated measurements of the DC output characteristics of the MOSFETs were performed and monitored over a period of one month. Variations within ±0.9 % of the drain current and ±0.2 % of the on-resistance were recorded, demonstrating a very high stability of such devices over time.**

***Index Terms*—Diamond, Hydrogenated diamond surface, MOSFET, Transfer doping.**

## I. INTRODUCTION

HIGH power and high frequency diamond-based Field Effect Transistors (FETs) have been widely investigated by several research groups and reported in the recent literature [1], [2]. The most studied structure of diamond FETs is based on the p-type conductivity of hydrogenated diamond surface (H-diamond) [1] - [9].

Despite the DC and RF performance reported in open literature for H-diamond FETs are extremely promising and well documented, reliability and stability of such devices still represent a critical issue in view of their actual usage in high-power/high-frequency amplifying subsystems [3], [10], [11]. A well-known limitation of the H-terminated diamond technology is the high sensitivity of its conduction properties to environmental conditions. A solution to this problem relies on the development of a suitable passivation layer of the free H-diamond surface, possibly providing further improvements in device performance. In this context, two strategies were explored. On the one hand, high dielectric constant insulators such as $Al_2O_3$, AlN, $HfO_2$, $Y_2O_3$, $TiO_2$ and $ZrO_2$ were extensively investigated due to their capability of providing a stronger coupling between the gate and the conductive channel [12] – [18]. On the other hand, high work function oxides such as $V_2O_5$, $MoO_3$, $ReO_3$ and $WO_3$ were also studied since they can induce a higher hole concentration to the H-diamond surface (transfer doping effect), thus improving the conductivity of the channel [11], [20] – [29]. However, in this latter case, an extensive investigation assessing the stability of thin oxide layers is mandatory in view of their application as gate insulator in MOSFET devices.

In this letter, we investigate on how the surface conductivity of H-diamond can be improved, preserved and stabilized by using a thin high work function oxide, i.e. $V_2O_5$, in combination with a high dielectric constant oxide, i.e. $Al_2O_3$. This technology was adopted to fabricate diamond Metal-Oxide-Semicondutor Field Effect Transistors (MOSFETs), in which a stable drain current is measured repeatedly over time.

## II. EXPERIMENTAL

Synthetic single crystal (100)-oriented diamond substrates, 4.5×4.5×0.5 $mm^3$ in size, were used. About 1 µm thick high-quality intrinsic single crystal diamond layers were homoepitaxially grown by microwave plasma-enhanced CVD technique. The surface of each diamond sample was then hydrogenated by $H_2$ plasma exposure.

In order to verify the reproducibility of the experimental results, different sets of samples were produced in this work,

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Manuscript received January 9, 2019. This work was supported in part by the Italian Space Agency (ASI) under the contract ReMiDA: Reliable Microwave devices on hydrogenated Diamond for space Applications.

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DOI: 10.1109/LED.2019.2903578

each one consisting of at least three nominally identical samples. Consistent values were always obtained among samples of the same type, so that we will refer to one sample per type from now on.

Two samples were coated with a very thin $V_2O_5$ layer (thickness ~ 7 nm) by thermal evaporation technique. In one of such samples the $V_2O_5$ layer was deposited just after the hydrogenation process without any preliminary treatment (no annealing), whereas for the other one an annealing in vacuum ($\approx 10^{-6}$ mbar) at 350 °C for 1 h was performed prior to oxide deposition. One more sample was prepared by depositing a 7 nm layer of $V_2O_5$ on the H-diamond surface annealed at 350 °C, followed by a 5 nm additional layer of $Al_2O_3$, deposited by electron beam evaporation technique.

The electrical characterization of the surface conductivity of the resulting CVD diamond samples was performed at RT by Hall-effect measurement in van der Pauw configuration by means of an Ecopia HMS 3000 HALL system. The electrical contacts were obtained by applying silver paint contacts to the corners of the samples [11], [23].

Stability in time of the conduction properties of the samples was investigated by monitoring the Hall parameters for one month. During the experiment, the samples were stored altogether in the same place, characterized by uncontrolled ambient atmosphere.

Diamond MOSFETs were then fabricated on H-diamond surface by standard photolithographic technique [26] - [30], by adopting the $V_2O_5/Al_2O_3$ bilayer as gate insulator. Gold (200 nm thick) and Aluminum (100 nm thick) were used as source/drain and gate contacts, respectively. The gate length and width was 2.6 µm and 100 µm, respectively. The source-drain distance was about 7 µm. The device was characterized in terms of DC characteristics over a period of one month.

## III. RESULTS AND DISCUSSION

The Hall measurement results, performed over a period of one month, are reported in Fig. 1. Immediately after the $V_2O_5$ deposition, a Hole concentration of $6\times10^{13}$ $cm^{-2}$ and $2.9\times10^{13}$ $cm^{-2}$ were obtained for the pre-annealed and the un-annealed sample, respectively. Such values are sensibly higher as compared to the value obtained with air doping [23], [24]. Such a behavior is due to the transfer doping mechanism introduced by the large $V_2O_5$ work function forcing electrons towards the insulator when brought in contact with the H-diamond. It's worth to point out that the transfer doping is more effective when the above described *in-situ* annealing is performed prior to the oxide deposition. This improvement is due to the removal of surface impurities adsorbed during the air exposure of the sample, so that a clean diamond/H/$V_2O_5$ interface is formed after the oxide deposition [11], [23], [25]. Test at different pre-annealing temperatures were also performed but not reported here. Experimental data showed similar Hall parameters for annealing temperatures ranging between 250 °C and 400 °C. A decrease of $V_2O_5$ transfer doping capability was instead observed when the annealing temperature is higher than 500 °C, likely due to a degradation of the H-terminated diamond surface.

During one month of air exposure, a noticeable decrease in sheet hole concentration was observed for all samples passivated with 7 nm of $V_2O_5$ (Fig. 1a) while an almost constant value of the hole mobility was recorded (Fig. 1b). The sheet resistance increased up to 11.5 kΩ/sq and 4.7 kΩ/sq for the not annealed and pre-annealed samples, respectively (Fig. 1c). It is worth to point out that the degradation observed in both the $V_2O_5$ passivated samples is much higher with respect to the ones reported in the literature for thicker $V_2O_5$ layers (100 nm) [11], [23]. Such a degradation may be attributed to the sensitivity of the oxide layer to atmosphere. In particular, $V_2O_5$ has been shown to be highly sensitive to air exposure, leading to a reduction of its work function [31] and a consequent decrease of the hole concentration at the $V_2O_5$/H-diamond interface.

To verify that the degradation of the Hall parameters is indeed due to air exposure, thus excluding other possible mechanism, a diamond sample with 7 nm of $V_2O_5$ pre-annealed at 350 °C was stored in vacuum, at a pressure of about $10^{-2}$ mbar. Hall parameters were acquired immediately after the oxide deposition, after 10 days and after 1 month (stars in Fig. 1). In this case, no variation of the Hall parameters was observed. In agreement with [11], this strongly suggests that a proper passivation of the $V_2O_5$ film is mandatory in order to stabilize the conduction properties of the diamond surface. This is why a third sample was prepared by depositing an additional 5 nm layer of $Al_2O_3$.

DOI: 10.1109/LED.2019.2903578

The obtained Hall parameters are also reported in Fig. 1 (open squares). Interestingly, the $Al_2O_3$ layer deposition does not affect the transfer doping capability of $V_2O_5$, being the resulting sheet hole concentration measured immediately after the deposition practically unchanged. In addition, $Al_2O_3/V_2O_5$/H-diamond structure exhibits a significant improvement in time stability, with no evident losses of doping efficiency over a period of one month. In particular, the mean value of the sheet hole concentration over one month is $5.6\times10^{13}$ cm$^{-2}$, with a standard deviation of about 2 %. The sheet resistance shows an average value of 3160 Ω/sq with a standard deviation of about 1 % and an even smaller variation in hole mobility is observed during one month.

A MOSFET adopting the $Al_2O_3/V_2O_5$ as gate insulator was then fabricated and characterized. The output DC characteristics of the devices are reported in Fig. 2. The device showed a saturation drain current density of -220 mA/mm at $V_{GS} = -4$ V and a maximum leakage gate current of about 25 µA/mm. The threshold voltage was +0.8 V and a maximum value of the transconductance of 62 mS/mm was obtained at $V_{GS} = -3$ V.

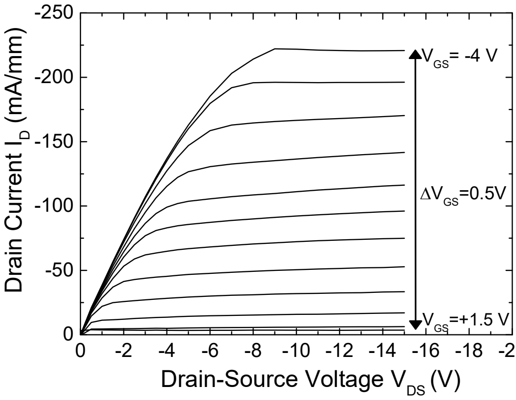

Fig. 2 - DC characteristics of the MOSFET.

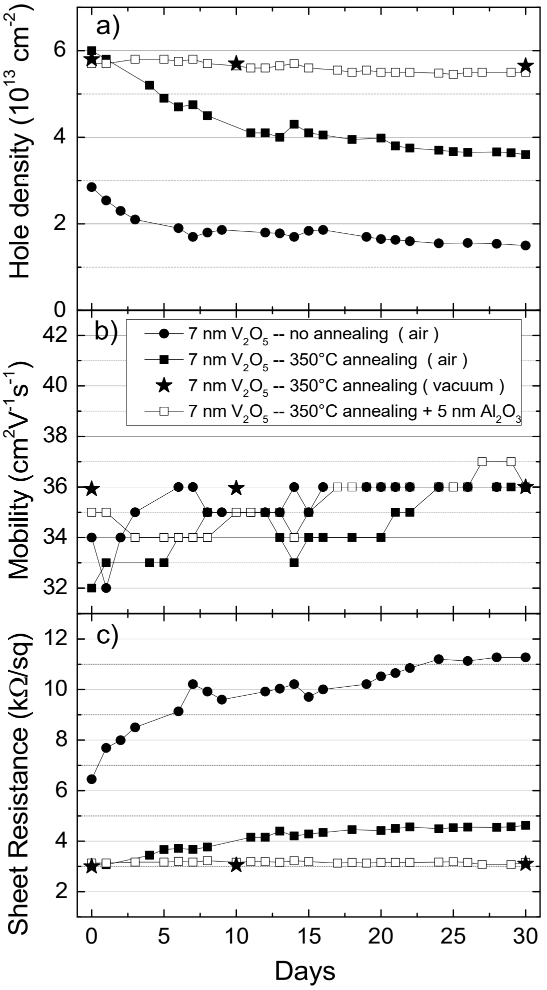

Fig. 1 - The doping stability of H-diamond surface: (a) sheet hole density, (b) hole mobility, and (c) sheet resistance.

To evaluate the stability of the MOSFET, repeated measurements of the output characteristics were performed. The current-voltage characteristics were measured successively for 20 times with $V_{GS}$ changing from 0 V to -3 V in 1 V steps and with $V_{DS}$ changing from 0 V to -20 V. Fig. 3 shows the results of repeated measurements of $I_D$–$V_{DS}$ characteristics altogether. No degradation in the drain current was observed during the repeated measurements and no significant trend of the $I_{DS}$ as a function of the repeated I-V sweeps was recorded. Therefore, the adopted $V_2O_5$ and $Al_2O_3$ bilayer was demonstrated to be stable and to act as a good potential barrier at the gate.

In order further evaluate the stability of the MOSFET, the same test was repeated once a week for four weeks. The average values of the drain current density and the corresponding $R_{ON}$ values at $V_{GS} = -3$V for each repeated measurement are summarized in Table 1.

For each measurement session, the standard deviation $\sigma_{ID}$ of the drain current density was less than 0.7 %, whereas the standard deviation $\sigma_{RON}$ of the ON resistance was lower than 0.4 %. This is a further indication that no degradation occurs during the repeated measurements of $I_D$–$V_{DS}$ characteristics.

DOI: 10.1109/LED.2019.2903578

In addition, a very good agreement, within ±0.9 % and ±0.2 % was found among the $<I_D>$ and $<R_{ON}>$ values measured over the whole investigated time lapse, indicating that the MOSFETs exhibit a quite good stability over time. Such an improved device stability is to be attributed to the addition of the $Al_2O_3$ layer properly passivating the underlying $V_2O_5$/H-diamond terminated surface and thus preventing the above reported degradation of the transfer doping effect due to air exposure.

TABLE I
DC PARAMETERS RECORDED OVER A PERIOD OF ONE MONTH.

| | $<I_D>$ (mA/mm) | $\sigma_{ID}$ (%) | $<R_{ON}>$ (Ω) | $\sigma_{RON}$ (%) |
|---|---|---|---|---|
| 1th week | 159.4 | 0.6 | 163.4 | 0.4 |
| 2th week | 161.2 | 0.5 | 162.7 | 0.4 |
| 3th week | 162.3 | 0.5 | 163.2 | 0.3 |
| 4th week | 159.7 | 0.7 | 162.8 | 0.4 |

## IV. CONCLUSION

The efficiency and long-term stability of the surface transfer doping induced by very thin $V_2O_5$ layer on H-terminated diamonds were investigated. The results demonstrate that the use of $Al_2O_3$ as an additional passivation layer preserves the surface transfer doping effect over time. H-diamond MOSFET with $V_2O_5$ /$Al_2O_3$ as gate insulator were fabricated, showing good performance and high stability. These results open the way to the design and realization of reliable high power amplifiers based on diamond field effect transistors.

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DOI: 10.1109/LED.2019.2903578