Electrical Characteristics of Al_2O_3/InSb MOSCAPs and the Effect of Postdeposition Annealing Temperatures

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***Abstract*— The characteristics of Al_2O_3/InSb MOSCAPs processed with different postdeposition annealing (PDA) temperatures are investigated. X-ray photoelectron spectroscopy analysis shows a significant reduction of InSb-oxides after HCl plus trimethyl aluminum treatment and oxide deposition. Multifrequency capacitance-voltage (C–V) characteristics exhibit low-frequency and asymmetrical C–V behaviors, in which capacitance in the InSb conduction band side is lower than in the valence band side. The electrical properties of the MOSCAPs are sensitive to PDA temperature and degraded significantly at PDA temperature >300 °C. This degradation is closely related to the diffusion of In, Sb into Al_2O_3 as indicated by transmission electron microscopy analyses.**

***Index Terms*— Al_2O_3, asymmetrical C–V, atomic layer deposition (ALD), InSb, MOS, post deposition annealing (PDA).**

I. Introduction

Besides the use in infrared imaging systems, high carrier mobility, narrow-gap InSb has drawn attention for its potential in extremely high-speed, low-power CMOS devices application such as nanowire, quantum well (QW) or band-to-band tunneling (T) field-effect-transistors (FETs). Among III–V compounds, InSb has the highest electron mobility of 7.7×10^4 $cm^2V^{-1}s^{-1}$ and hole mobility of 840 $cm^2V^{-1}s^{-1}$ [1], which promise of both n- and p-channel high-performance transistors. InSb-based QWFETs demonstrated very-high speed performance at low supply voltage (0.5 V) for both n- and p-channels devices [2], [3]. The integration of InSb on Si for MOS devices application was also reported [4]. For both infrared and CMOS applications, the deposition of dielectric layer with good quality interfacial properties is essential for the effective performance of devices. Several methods such as anodic oxidation, plasma-enhanced chemical vapor deposition (PECVD), remote PECVD, and low-temperature chemical vapor deposition are used to deposit the insulator/oxide layer on InSb for studying. However, the study of InSb MOS capacitors (MOSCAPs) using atomic layer deposition (ALD) oxide is still seldom [4]–[7]. The ALD method is well known to be a robust and manufacturable process, which is promising for manufacturing of CMOS technology. Because InSb has low thermal budget [1], the electrical characteristics of the ALD oxide/InSb MOSCAPs are sensitive to thermal processes. In this paper, the electrical properties of ALD Al_2O_3/InSb MOSCAPs and their dependent on postdeposition annealing (PDA) temperatures are studied. The multifrequency asymmetrical C–V behavior of Al_2O_3/n-InSb MOSCAPs due to the low density of state (DOS) in InSb conduction band is experimentally observed in this paper. The out diffusion of In, Sb atoms into Al_2O_3 is found to be the major effect on the electrical degradation of the MOSCAPs such as hysteresis, frequency dispersion, C–V modulation, C–V stretch-out, and interface density of states D_{it}.

II. Materials and Experiment

Wafers used in this research are InSb (100) undoped substrate, naturally n-type behavior with donor concentration of 2.2×10^{16} cm^{-3} at room temperature, determined by Hall measurement. The wafers are initially degreased by rinsing in acetone and isopropanol for 2 min each. The samples are dipped in the diluted HCl 4% solution for 2 min, rising in deionized water, and blown dry by N_2 gas. The samples are then loaded into ALD chamber (Cambridge NanoTech Fiji 202 DSC) within 5 min after cleaning. In ALD chamber, the samples are precleaned by using ten pulses of trimethyl aluminum (TMA)/Ar [8]–[10] before the deposition of 85 cycles

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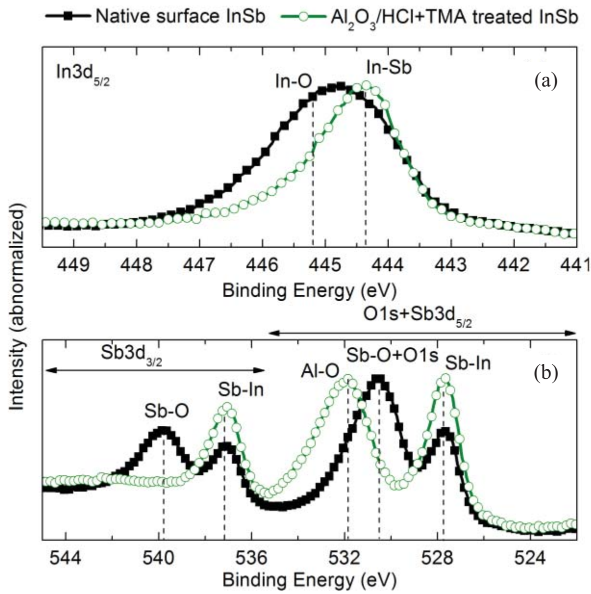

Fig. 1. (a) In $3d_{5/2}$ and (b) Sb 3d plus O1s XPS spectra of native InSb surface and 1.5-nm Al_2O_3/InSb interface.

(∼7.5 nm) Al_2O_3 at 250 °C, using TMA and H_2O as precursors. The HCl plus TMA treatment is proved to improve effectively Al_2O_3/InAs interface [8], [9]. The effect of TMA treatment in the reduction of InSb native oxides is also reported [5]. The samples are PDA at different temperatures of 300 °C, 350 °C, and 400 °C in N_2 for 30 s. Ni/Au metal gate is formed via photolithography/e-beam evaporation/liftoff process. Finally, Au/Ge/Ni/Au is deposited for backside ohmic contact followed by postmetal annealing at 250 °C in N_2 for 30 s. The multifrequency C–V is measured by an HP4284A LCR meter. The quasistatic C–V (QSCV) curves are performed using an Agilent B1500A semiconductor device analyzer. The chemical and structural properties of Al_2O_3/InSb interface are studied by X-ray photoelectron spectroscopy (XPS) measurement using a commercial Microlab 350 XPS system and transmission electron microscopy (TEM) using a Philips Tecnai F-20 microscope with energy-dispersive X-ray spectroscopy (EDS) analysis.

III. Results and Discussion

Fig. 1 shows In $3d_{5/2}$ and Sb 3d plus O 1 s XPS spectra of native InSb surface and the 1.5-nm ALD Al_2O_3/HCl plus TMA-treated InSb interface. The O 1 s peak overlapped with the Sb $3d_{5/2}$-related oxides peak. After surface treatment and oxide deposition, In-oxides are reduced significantly as shown in In $3d_{5/2}$ spectra [Fig. 1(a)]. The Sb $3d_{3/2}$ spectra in Fig. 1(b) show the reduction of Sb-related oxides below the XPS detection level. The O 1 s plus oxidized Sb $3d_{5/2}$ peak originally assigned to O–Sb and O–In bonds shifted to higher binding energy, which is mostly attributed to Al–O bonds. Similar O 1s peak position corresponding to Al–O bonds is also obtained by *in situ* XPS measurement of 1-nm ALD Al_2O_3/ammonium sulfide-treated InSb [11].

Fig. 2(a) shows the typical C–V behavior of the MOSCAPs at frequency of 1 MHz. The observed low-frequency C–V response at high frequency of 1 MHz is due to the high intrinsic carrier density n_i in InSb material [$n_i \sim 2 \times 10^{16}$ cm^{-3} at room temperature (RT)] [1]. The relation between n_i and the minority carrier response time τ_R is given by [10]

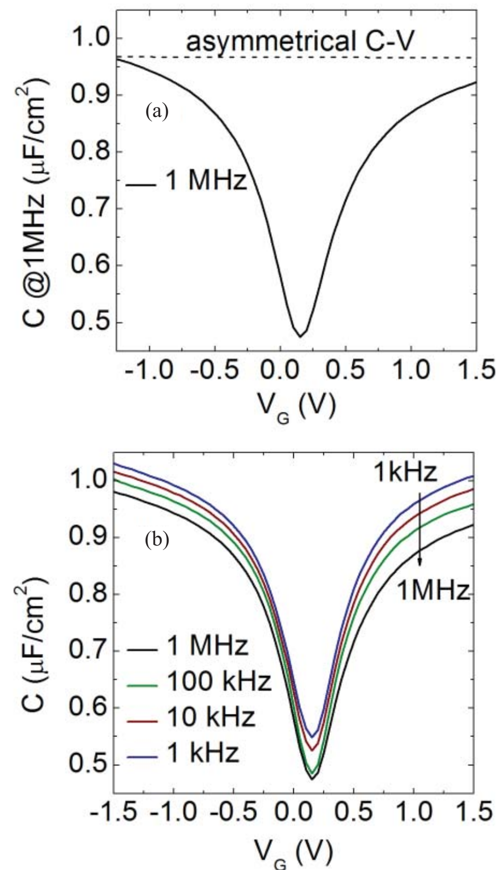

Fig. 2. (a) Typical low-frequency asymmetrical C–V response at 1 MHz. (b) Typical multifrequency C–V responses of Al_2O_3/InSb MOSCAP structure.

TABLE I
Parameters of InSb Used in (1) [1]

t_{Tn} (s)	t_{Tp} (s)	N_D (cm^{-3})	n$_i$ (cm^{-3})	N_C (cm^{-3})	N_V (cm^{-3})
5×10^{-8}	5×10^{-8}	2.2×10^{16}	2×10^{16}	4.2×10^{16}	7.3×10^{18}

$$\tau_R = \frac{1}{\sqrt{2}} \frac{N_D}{n_i} \tau_T \left(1 - \frac{\upsilon_T}{u_B}\right)^{1/2} \quad (1)$$

where N_D is donor doping density, $\tau_T = \sqrt{\tau_{\mathrm{Tn}}\tau_{\mathrm{Tp}}}$ (τ_{Tn} and τ_{Tp} are bulk electron and hole life times), υ_T and u_B are potentials above the intrinsic level of bulk trap and Fermi levels in InSb [9]. By taking the parameters in Table I [1], the value of τ_R in InSb estimated by (1) is of 3.9×10^{-8} s at room temperature. This very short response time would allow minority carriers to response to such high-frequency ac signal as 1 MHz.

The asymmetrical C–V curve, in which the capacitance on the InSb conduction band side is lower than on the valence band side, is also observed obviously in Fig. 2(a). To our knowledge, this observation is first time witnessed by experimental high-frequency C–V measurement. The observation at high frequency of 1 MHz is due to the observation of low-frequency C–V response in InSb-based MOSCAPs as

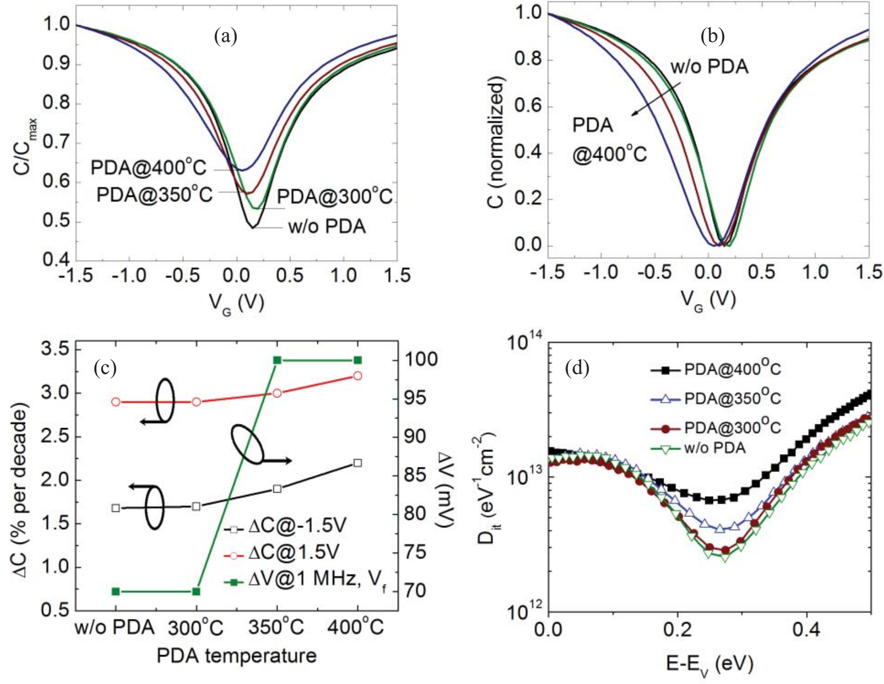

Fig. 3. (a) $C/C_{\max} - V$. (b) Normalized C–V characteristics at 1 MHz of the Al_2O_3/InSb MOSCAPs with different PDA temperatures. (c) Frequency dispersion, hysteresis. (d) Interface trap profiles of the MOSCAPs increase significantly at PDA temperature greater or equal to 350 °C.

discussed above and a very low DOS in InSb conduction band (N_C). At RT, the value of N_C is 4.2×10^{16} cm^{-3}, which is 170-fold lower than N_V (7.3×10^{18} cm^{-3}) [1]. This low value of N_C would lead to the semiconductor capacitance C_s could not be very large compared with oxide capacitance C_{ox}, and thus results in lower the total capacitance C_{tot} in the conduction band side according to the following equation [12]:

$$C_{tot} = C_{ox}\left(1 + \frac{C_{ox}}{C_s + C_{tr}}\right)^{-1} \tag{2}$$

where C_{tr} is capacitance by the traps at/near Al_2O_3/InSb interface.

The typical multifrequency C–V response of Al_2O_3/InSb MOSCAPs is shown in Fig. 2(b). At low frequency, the asymmetrical C–V behavior becomes less significant that implies the increase of the contribution of C_{tr} to the C_{tot} with the decrease of the measuring frequency [see (2)]. For narrow gap semiconductor as InSb, the interface traps response time is so short that it can follow the ac signal with frequency in the range 1 kHz to 1 MHz [13]. In this context, the increase of C_{tr} with the decrease of measuring frequency might come from the interaction of traps located inside oxide (called border traps) with conduction band electrons via tunneling [13].

Fig. 3 shows the comparison of samples underwent various PDA temperatures. The C/C_{max}–V responses at 1 MHz of samples are shown in Fig. 3(a). The modulation of C–V curves is less significant with the increase of the PDA temperatures. Fig. 3(b) and (c) shows the increase significantly of C–V stretch-out, frequency dispersion, and hysteresis when the PDA temperature is greater than or equal to 350 °C. The C–V stretchout is caused by the slow interface/border traps that could not follow the ac signal but do follow the dc bias sweep [14]. The degradation of C–V stretchout is significant in the negative gate bias side [Fig. 3(b)] shows a noticeable increase of the donor-like interface/border traps at the PDA temperature of 350 °C and above. To quantify the degradation, the interface traps are extracted by low-frequency C–V fitting method by self-consistent solution of Schrodinger–Poisson equations, similar to the approach in [15] and [16]. Initially, the semiconductor capacitance C_S is extracted by solving the Schrodinger–Poisson equations of the Al_2O_3/InSb ideal MOS structure (without interface density). The capacitance due to interface traps of the real MOS structure (C_{it}) is calculated by from the following equation [17]:

$$C_{it} = \frac{C_{ox}C_{mes}}{C_{ox} - C_{mes}} - C_S \tag{3}$$

where, C_{ox} is the oxide capacitance and C_{mes} is experimental QSCV data. From this value, the simulated C–V curve is extracted and compared again with the experimental C–V curve. Some parameters of the MOS structures such as flat band voltage (V_{fb}) and charge neutral level (E_{CNL}) are modulated by the simulation and the D_{it} profile is extracted when the best fit between simulating and experimental C–V is occurred. The traps energy level E is defined from the equation [15], [16]

$$E - E_C = E_g + E_F - q\varphi_s \tag{4}$$

where E_C, E_g, and E_F are conduction band minimum level, band gap, and Fermi level in InSb, respectively, and φ_s is surface potential. The surface potential is determined from the gate bias V_g given by

$$\varphi_s = V_g - V_{fb} + \frac{Q_s + Q_{it}}{C_{ox}} \tag{5}$$

where Q_s and Q_{it} are the semiconductor charge and interface trap charge, respectively. The D_{it} profiles are similar for the

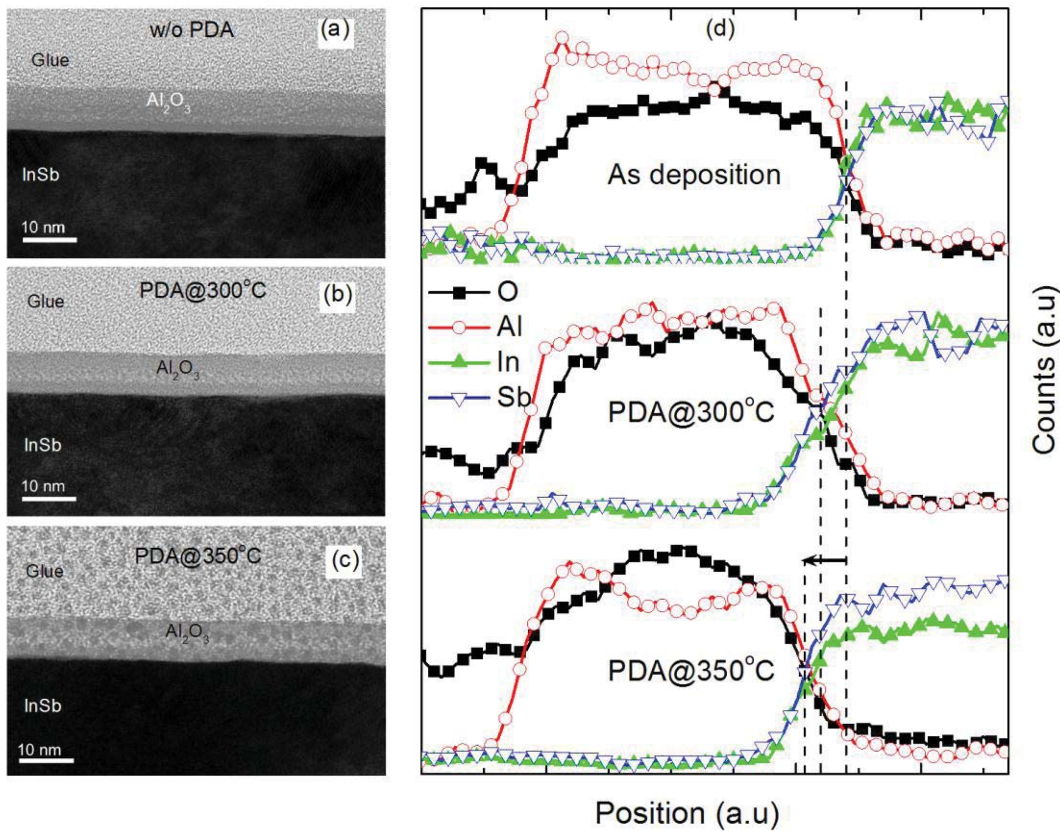

Fig. 4. TEM images of the Al_2O_3/InSb structures. (a) After oxide deposition. (b) PDA at 300 °C, 30 s. (c) PDA at 350 °C, 30 s. (d) EDS spectra of the samples.

samples without PDA and PDA at 300 °C with minimum value of 2.55×10^{12} $\mathrm{eV^{-1}cm^{-2}}$ at trap position $E{-}E_V$ = 0.275 eV as shown in Fig. 3(d). Simultaneously, the minimum of D_{it} levels of the samples which went through PDA at 350 and 400 °C increases significantly with increasing PDA temperatures.

The high-resolution transmission electron microscopy analyses of 7.5-nm Al_2O_3/InSb as dep, PDA at 300 °C and 350 °C are shown in Fig. 4 (the TEM figure of the sample PDA at 350 °C is the spotted through the use of Pt for preventing the sample's damage). From the high-resolution cross-sectional TEM image in Fig. 4(a), it is clearly shown that the as deposited sample exhibits a double-layer gate oxide with thickness of 1.5 nm/6 nm. The 1.5-nm layer is attributed to the out diffusion of In, Sb into Al_2O_3 during the 1 h suffered at 250 °C oxide deposition process. The out-diffusion layer increases with the increasing of PDA temperatures as indicated in Fig. 4(a)–(c). The EDS analysis of the samples shown in Fig. 4(d) also indicates the increase of In, Sb out-diffusion into Al_2O_3 with the increasing of PDA temperatures. This strong out-diffusion would result in the degradation of Al_2O_3/InSb interface as well as Al_2O_3 oxide itself, which leads to the degradation of the electrical properties of the MOSCAPs as discussed above.

IV. Conclusion

In conclusion, we discussed the electrical properties of Al_2O_3/InSb MOSCAPs and their dependent on PDA temperature. The low-frequency asymmetrical C–V behavior was experimentally observed at high-frequency C–V measurement because of the short minority carrier response time and low DOS in InSb conduction bandgap. When the PDA temperature was increased to 350 °C and above, the electrical properties of the MOSCAPs degraded significantly. This degradation was due to the strong out diffusion of In, Sb atoms into the Al_2O_3 oxide layer with the increase of PDA temperature proved by TEM and EDS analyses.

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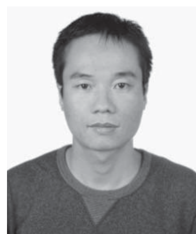

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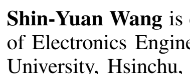

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