Applied Surface Science 254 (2008) 6063–6066

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Surface passivation of InGaP/GaAs HBT using silicon-nitride film deposited by ECR–CVD plasma

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ARTICLE INFO

Article history:
Available online 21 March 2008

PACS:
71.55.Eq

Keywords:
Silicon-nitride film
Passivation
ECR–CVD plasma
HBT

ABSTRACT

In this paper we have developed a passivation technique with silicon-nitride (SiN_X) film that requires no surface pre-treatment, and is fully compatible to monolithic microwave integrated circuits (MMICs). The nitride depositions were carried out by ECR–CVD (electron cyclotron resonance–chemical vapor deposition) directly over InGaP/GaAs heterojunction structures, which are used for heterojunction bipolar transistors (HBTs). Optical emission spectrometry (OES) was used for plasma characterization, and low formation of H and NH molecules in the gas phase was detected at pressure of 2.5 mTorr. These molecules can degrade III–V semiconductor surfaces due to the preferential loss of As or P and hydrogen incorporation at the substrate. The substrates were cleaned with organic solvents using a Sox-let distillate. The ECR depositions were carried out at a fixed substrate temperature of 20 °C, SiH_4/N_2 flow ratio of 1, Ar flow of 5 sccm pressure of 2.5 mTorr and microwave (2.45 GHz) power of 250 W and RF (13.56 MHz) power of 4 W. We have applied this film for InGaP/GaAs HBT fabrication process with excellent results, where two major contribuiton is related to this passivation technique, the enhancement in the transistor dc gain β and the improvement in the signal-to-noise ratio when compared unpassivated and passivated devices.

1. Introduction

Although GaAs has excellent mobility characteristics, which translates into faster circuits, the poor surface quality has prevented it from larger scale utilization as opposed to Si. Also, the development of good-quality MIS (metal–insulator–semiconductor) structures on GaAs has been hampered due to the lack of a suitable insulator [1]. Usually, this problem is addressed by surface passivation through deposition of a thin nitride film. This process requires prior surface treatment of NH_3 and/or H_2 and/or N_2 plasmas in order to remove native oxide [2,3] and fill the surface dangling bonds forming an ultra-thin GaN layer. Moreover, the nitride film is frequently deposited on a thin layer of Si over GaAs in order to take advantage of the well-known Si oxides. Furthermore, SiH_4 and/or NH_3 and/or N_2 gas sources, which have been used in electron cyclotron resonance–chemical vapor deposition (ECR–CVD) plasma reactors, to obtain the silicon-nitride (SiN_X) passivation layer, can degrade the III–V semiconductor surfaces (such as GaAs substrates and AlGaAs/GaAs or InGaAs/InP heterostructures) due to the preferential loss of As or P (enhanced by ion bombardment at pressures higher than 10 mTorr) and the hydrogen incorporation at heterojunction bipolar transistor (HBT) emitter and base areas or substrates. This degradation can be from high H and NH molecule formation in the gas phase at pressures higher than 10 mTorr during the ECR–CVD deposition [2,3].

In this paper we have developed a passivation technique with silicon-nitride film that requires no surface pre-treatment, and is fully compatible to monolithic microwave integrated circuits (MMICs). The nitride depositions were carried out by ECR–CVD directly over InGaP/GaAs heterojunction structures, which are used for HBTs.

2. Passivation on HBT transistors

Two types of HBTs were developed for this study, a passivated structure (with silicon-nitride film) and an unpassivated structure (without silicon-nitride film). The silicon-nitride film deposited by ECR–CVD was carried out at a fixed substrate temperature of 20 °C, SiH_4/N_2 flow ratio of 1, Ar flow of 5 sccm, pressure of 2.5 mTorr and microwave (2.45 GHz) power of 250 W and RF (13.56 MHz) power of 4 W. This film was deposited over the whole passivated

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0169-4332/$ – see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.apsusc.2008.02.187

Table 1
Detailed HBT structure

Layer	Material	Thickness (nm)	Doping (cm^{-3})
Cap	$In_yGa_{1-y}As$ ($y = 0.5$)	50	$>1.0 \times 10^{19}$ (n^+)
Cap	$In_yGa_{1-y}As$ ($y = 0$–0.5)	50	$>1.0 \times 10^{19}$ (n^+)
Cap	GaAs (Si)	100	5.0×10^{18} (n^+)
Emitter	$In_yGa_{1-y}P$ ($y = 0.5$) (Si)	50	5.0×10^{17} (n)
Base	GaAs (C)	80	4.0×10^{19} (p^+)
Collector	GaAs (Si)	500	4.0×10^{16} (n^+)
Sub-collector	GaAs (Si)	500	5.0×10^{18} (n^+)

structure before the interconnection isolation process. The detailed composition of each layer is shown in Table 1. The fabrication process is very similar to the one described for AlGaAs/GaAs HBTs in [4] except that a 60 nm silicon-nitride layer was deposited over the whole device before the interconnection isolation process. The nitride processed without H_2 and N_2 plasma surface pre-treatment was employed. Then via-holes are opened by plasma etching. The final structure is depicted in Fig. 1(a) and a top side view optical micrography in Fig. 1(b). The transistors generated had $20\ \mu m \times 6\ \mu m$ and $20\ \mu m \times 16\ \mu m$ emitter area sizes and all HBTs studied are non-self-aligned structures. Comparisons between passivated and unpassivated transistors are performed.

3. Results and discussion

Four different pressure process conditions were used for nitride deposition: 2.5, 5.0, 10 and 15 mTorr. Emission lines of Si (288 nm), H_β (484 nm), N_2 (358 nm) and NH (336 nm) were identified by optical emission spectroscopy (OES) measurements. These values were obtained for a spectral range of 200 and 900 nm and normalized for Ar (750 nm). Fig. 2 presents emission ratios of Si (288 nm)/Ar (750 nm), H_β (484 nm)/Ar (750 nm), N_2 (358 nm)/Ar (750 nm) and NH (336 nm)/Ar (750 nm) with pressure ranging from 2.5 to 15 mTorr.

From Fig. 2 we may observe:

(i) Si emission increases until pressures of 10 mTorr, then it is about constant as pressure increase;
(ii) N_2 emission decrease with pressure;
(iii) H_β emissions are about constants, change only slightly for pressure higher than 10 mTorr;
(iv) NH emission increase with pressure;
(v) NH molecule formation and the increase of Si and H_β emission (identified in (i) and (iii), respectively) for pressures higher than 5.0 mTorr, may be attributed to high dissociation level of SiH_4 molecules under high power discharge of the ECR plasmas, which allow the N and H interaction during plasma gas phase. These NH radicals may contribute to formation of poor qualities silicon-nitride films, which is undesirable.
(vi) All emission line presents low intensity for pressure of 2.5 mTorr. This condition is primordial for GaAs surface passivation using silicon nitride.

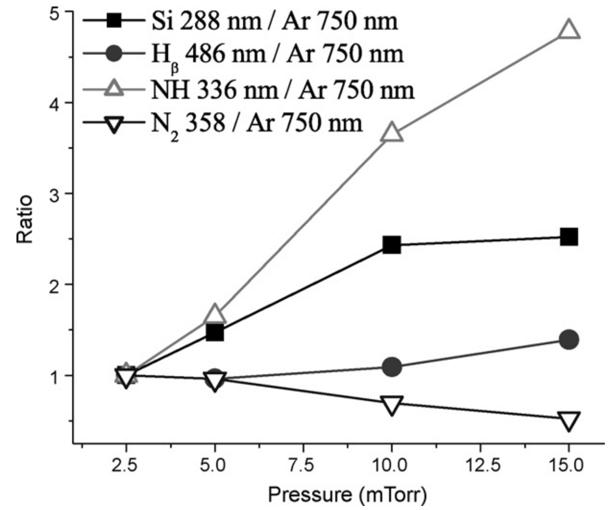

Fig. 2. ECR plasma emission ratios: Si (288 nm)/Ar (750 nm), H_β (484 nm)/Ar (750 nm), N_2 (358 nm)/Ar (750 nm) and NH (336 nm)/Ar (750 nm) during the silicon-nitride deposition process for different pressure [5].

In analysis of Fig. 2 one can observe that transistors fabricated at pressures greater than 5 mTorr do not exibit good results. Later this was confirmed by capacitors $C \times V$ measurements. Therefore, the lowest pressure used here (2.5 mTorr) favors an efficient generation of atmic H and N (and, probably, their ions) together with SiH_3 radicals rather than unsaturated SiH_x ($x < 2$) radicals, which are known to have high sticking coefficient and low surface mobility and thus contibute to production of porous nitride films.

3.1. Electrical measurements

The transistor emitter area sizes were of $20\ \mu m \times 6\ \mu m$ and $20\ \mu m \times 16\ \mu m$ and all HBTs studied are non-self-aligned structures. In the unpassivated devices the surface states represent an escape route for carriers being injected from the emitter. Such carriers recombine at these states without contributing to the collector current. This is confirmed in Figs. 3 and 4 which show the Gummel Plot for passivated and unpassivated HBT transistor with emitter area sizes were of $20\ \mu m \times 6\ \mu m$ and $20\ \mu m \times 16\ \mu m$, respectively. In both cases, for $V_{BE} = 1.3$ V or higher, the passivated

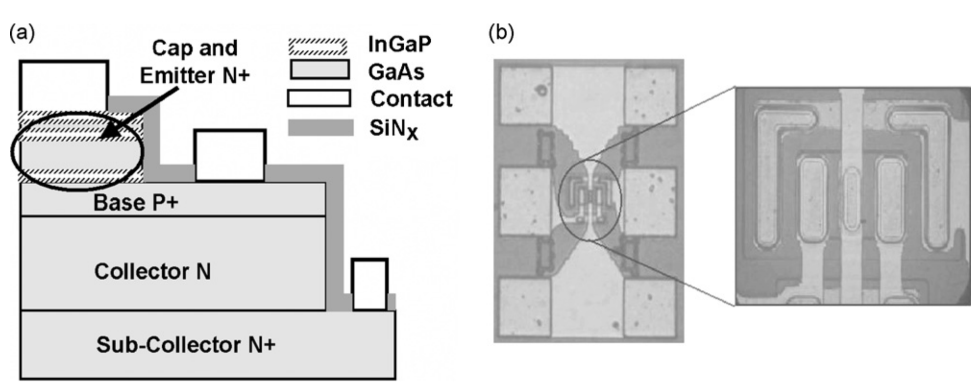

Fig. 1. Passivated structure: silicon-nitride film (as passivation layer) deposited on the InGaP/GaAs HBTs devices by ECR plasma processing. (a) HBT structure layer. (b) HBT top side view of $20\ \mu m \times 6\ \mu m$ emitter area [5].

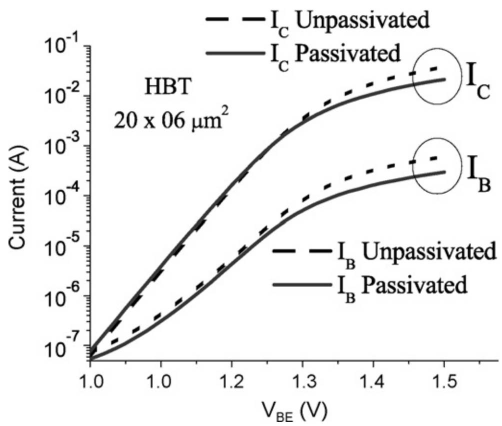

Fig. 3. Passivated and unpassivated 20 μm × 6 μm emitter area size HBTs Gummel Plot.

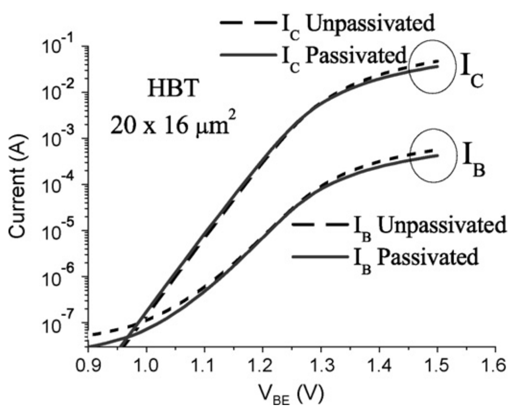

Fig. 4. Passivated and unpassivated 20 μm × 16 μm emitter area size HBTs Gummel Plot.

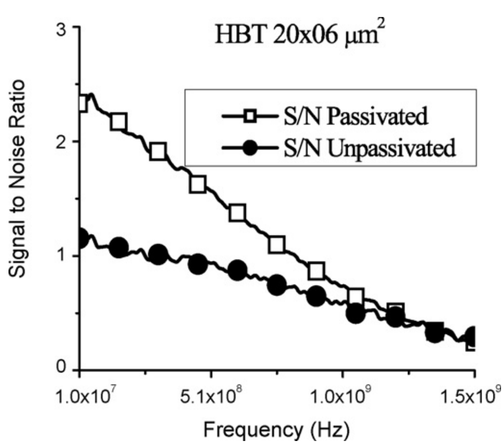

Fig. 5. Signal-to-noise ratio of passivated and unpassivated HBTs—20 μm × 6 μm emitter area size.

transistor base current is lower than unpassivated transistor base current, and in collector current this occurs only in high current regions, where second-order effects appear and surface currents are less pronounced. This difference reflects in transistor dc gain β, where $\beta = I_C/I_B$. Passivated transistor gains are 72 and 86 for emitter areas sizes of 20 μm × 6 μm and 20 μm × 16 μm, respectively. These gain values are higher than the presented values of unpassivated transistor of 64 and 84, respectively.

Another key point in this passivation technique regarding the improvement in the noise, figure of the HBTs [6], is shown in Figs. 5 and 6. The signal-to-noise ratio presents excellent results and an enhancement of more than twice was obtained when compared passivated and unpassivated devices, respectively. As frequency increases, this effect becomes less pronounced due to lowering in the surface recombination current rate. So this passivation technique is important for devices that work in low bias condition. It is not clear why collector current decreases in high current region. Ref. [6] reported similar results (Table 2).

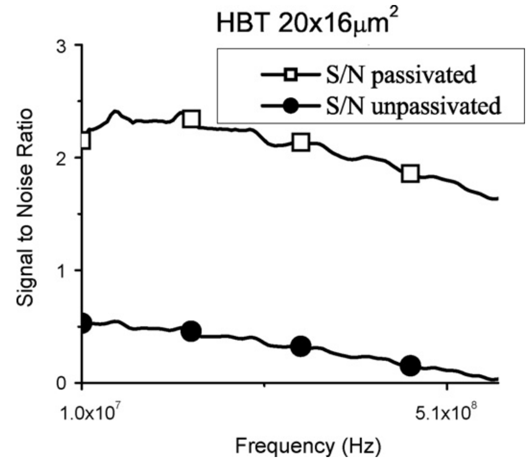

Fig. 6. Signal-to-noise ratio of passivated and unpassivated HBTs—20 μm × 16 μm emitter area size.

Table 2
dc bias used in the signal-to-noise ratio measurements

Emitter area	dc bias							
	V_{CE} (V)		I_C (mA)		V_{BE} (V)		I_B (μA)	
	[P]	[UP]	[P]	[UP]	[P]	[UP]	[P]	[UP]
20 μm × 6 μm	2.50		1.16	0.35	1.25	1.22	7	
20 μm × 16 μm	2.50		0.81	0.28	1.22	1.20	11	

[P]: passivated transistor; [UP]: unpassivated transistor.

The negative values observed in Fig. 6 are due to the gain lowering of the transistors. For larger area transistor the unit gain frequency is lower. This also explains the difference between Figs. 5 and 6.

4. Conclusions

These electrical properties indicate that the silicon-nitride films have presented high quality, with excellent InGaP/GaAs surface passivation. A simple and comprehensive study of the device's current was conducted whereby it was determined that surface recombination current plays a critical role in device performance. This feature is of great value in the design of low noise, low power consumption, high quality circuits, a key point in today's telecommunication industry.

Acknowledgments

The authors would like to thank CNPq and CAPES of Brazil for financial support.

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