Nonalloyed Refractory Metals for Self-Aligned InP HBT Emitter Contacts with InAs/InGaAs Emitter Cap

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Keywords: HBT, Refractory, Emitter, Contact, Self-aligned

Abstract

Nonalloyed refractory emitter contacts for a self-aligned sub-micron InP HBT process have been fabricated. The contacts are annealed up to 420°C and characterized through TLM measurements and SEM examination. It is found that the inclusion of refractory metals such as Mo, W, and TiW effectively increased the stability and integrity of emitter contacts when subjected to high temperatures.

INTRODUCTION

The InP HBT is an important device technology because it offers a combination of high speed (f_T/f_{MAX}), high gain, and high breakdown voltage. It has found wide applications in RF, mixed-signal IC, and communication instrumentation [1]. Recently, a Type-II InP/GaAsSb DHBT has demonstrated f_T/f_{MAX} = 480/620GHz with maximum current gain β of 24 and BV_{CEO} of 6.3V [2]. In order to make 600GHz InP HBTs more attractive for higher level integration in wide-dynamic mixed signal circuits against 300GHz SiGe BiCMOS, further improvements are needed in device scaling, linearity, reliability and manufacturability. A prominent problem for InP HBTs is surface recombination between the base contact and the emitter mesa which leads to gain degradation in devices with small emitters, called the emitter size effect [3]. Several methods have been investigated to mitigate this issue such as passivation using an emitter ledge [2]. Other passivation solutions involve device treatment at elevated temperatures such as hydrogen removal from a carbon doped base [4] and capping of the extrinsic base region using thermal atomic layer deposited Al_2O_3 [5].

Currently, techniques that involve high temperature annealing are done in devices where the emitter mesa is defined by lithography and the emitter metallization is done post-anneal. These techniques are not suitable for self-aligned HBTs where the emitter metal is deposited as the first step because the high temperature treatment promotes diffusion of the emitter metal into the semiconductor. This metal diffusion is a critical problem for typical nonalloyed contacts such as Ti/Pt/Au as it degrades the electrical characteristics of the emitter layer and may cause base-emitter shorts in the case of a thin emitter device. In addition, it has been demonstrated that when HBTs are operated at high current densities, elevated junction temperatures lead to rapid device degradation by the same mechanism [6].

A nonalloyed refractory emitter contact is desirable because of three reasons: first, it enables a self-aligned process to minimize the distance between the emitter mesa and the base contact to maximize high speed performance. Second, it is robust enough to withstand post-metallization high temperature processes. Third, it increases device reliability and makes the device less susceptible to thermal aging. In this work, metal stacks based on Mo, W, and TiW are evaluated. The refractory metallization process is designed to be compatible with a lift-off process for a sub-micron HBT with emitter widths up to 250 nm.

HBT LAYER STRUCTURE AND METAL DEPOSITION PROCESS

The emitter contacts are deposited on MBE-grown InP DHBT substrates similar to [2]. The emitter cap layer consists of a 15 nm thick InAs cap followed by a 25 nm composition-graded layer of $In_xGa_{1-x}As$ (x=1 to 0.53) on top of a 35 nm thick InP emitter and a GaAsSb base. TLM structures for contact and sheet resistivity measurement were patterned using optical lithography. Also, sub-micron HBT emitters between 0.25 µm x 8 µm and 0.4 µm x 8 µm were patterned using e-beam lithography to determine adhesion and integrity of annealed contacts on small emitters. After metal deposition and lift-off, the InAs/InGaAs cap layer and the InP emitter were wet etched using H_2O_2:$C_6H_8O_7$ and HCl, respectively, forming an undercut for the emitter mesa. This structure is identical to a self-aligned HBT emitter prior to base metallization. The samples were then capped with a 100nm film of 240°C PECVD silicon nitride to prevent As outgassing during annealing. In order to replicate post-emitter metal high temperature processing conditions, the samples were annealed in a dry N2 furnace at 420°C for 60 minutes with 20 minute ramp times from a resting temperature of 300°C. Subsequently, the silicon nitride is removed using CF_4 RIE.

The refractory contacts investigated in the work are Ti/Pt/W/Au, Ti/Pt/Mo/Au, Mo/Ti/Pt/Au, W/Ti/Pt/Au, Mo/Ti/Au, and TiW/Ti/Au. The standard Ti/Pt/Au contact is included as a benchmark for contact resistivity and sheet resistivity. Ti is used as the bottom layer in a Ti/Pt/Au contact to ensure good adhesion to

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the InAs/InGaAs cap. At high temperatures, Ti has been known to diffuse into the semiconductor [6], so a very thin Ti adhesion layer (10 nm) was used to minimize this effect. Refractory metals were inserted as a diffusion block for Au directly on the semiconductor or on top of a Ti/Pt adhesion layer.

The metal contacts were deposited using electron beam evaporation (Ti, Pt, Au) and DC sputtering (Mo, W, TiW). Due to the high temperatures during sputtering, only a small (< 20 nm) layer of refractory metal can be deposited without introducing a significant amount of e-beam resist pullback, which significantly enlarges the sub-micron emitters as shown in Fig. 1.

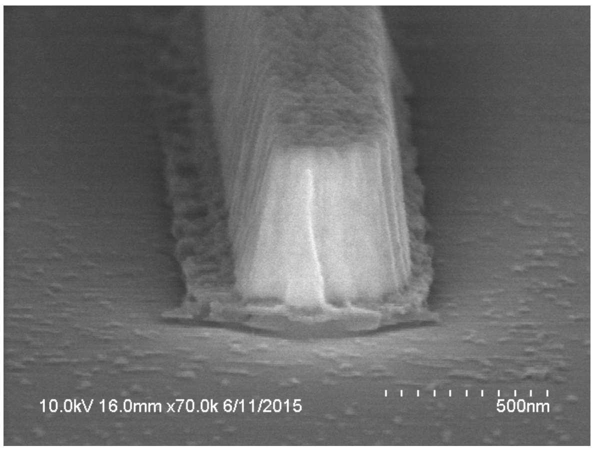

Fig. 1. Ti/Pt/W/Au emitter with a 350 nm thick W layer after emitter etch. The emitter has an enlarged footprint most likely due to e-beam resist pullback during the high temperature sputtering of W.

Characterization of Contacts

The characterization of the contacts is divided into two parts. First, the contact pads are measured using TLM. To determine contact resistivity and sheet resistivity. The contact pads are 80 µm x 80 µm with spacings of 5, 10, 15, 20, 25, and 30 µm. The TLM measurement is done on a DC probe station using Agilent E5287A and E5280B SMUs connected to an E5270B measurement mainframe. 16 identical TLM pads were measured for each metal stack and averaged to extract resistivity values. TLM measurements were also done on the contacts before annealing to establish a control group. Second, samples were observed under SEM to observe the adhesion of the emitter contacts on the semiconductor.

Table 1. Sheet resistivity and contact resistivity of annealed contacts. All contacts show very similar characteristics before annealing.

Metal Stack	Thickness (nm)	Sheet Resistivity (Ω-sq)	Contact Resistivity (Ω-µm2)
Control	10/10/150	17	216
Ti/Pt/Au	10/10/150	1.68	890
Ti/Pt/W/Au	10/10/10/150	15	10,000
Ti/Pt/Mo/Au	10/10/10/150	14	4,900
Mo/Ti/Pt/Au	10/10/10/150	19	3,160
W/Ti/Pt/Au	10/10/10/150	N/A	N/A
Mo/Ti/Au	10/10/150	20	414
TiW/Ti/Au	10/10/150	17	450

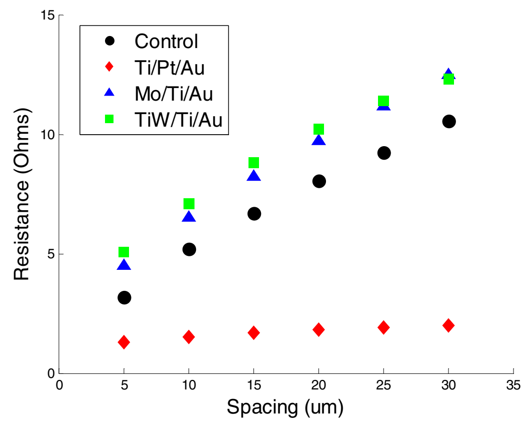

Fig. 2 (Color online). Measured TLM resistances for the Ti/Pt/Au, Mo/Ti/Au, and TiW/Ti/Au contacts after annealing.

Results

The contact resistivity and sheet resistivity of the metal contacts after annealing are shown in Table 1. Before annealing, all metal stacks display identical characteristics to Ti/Pt/Au with sheet resistivity of 17 Ω-sq and contact resistiviy of 216 Ω-µm^2. After annealing, Ti/Pt/Au shows a large reduction in sheet resistivity from 17 Ω-sq to 1.68 Ω-sq, indicating significant diffusion of the contact metal to the semiconductor substrate. Contacts with refractory metal deposited between Ti/Pt and Au show similar sheet resistivity values to the non-annealed case, but the contact resistivity values for these contacts are larger by a factor of over 20, which is undesirable because it would result in a very large emitter resistance. It was suspected that stress due to thermal expansion between the refractory and non-refractory metals played a part in the contact resistivity degradation.

With Mo deposited directly on the InAs/InGaAs cap with Ti/Pt/Au on top, the contact resistivity was slightly reduced but still far above the non-annealed case. It was found that W adheres poorly to the cap layer and no meaningful TLM measurements could be gathered from the W/Ti/Pt/Au contact. When W was replaced by a 10%-90% TiW alloy as the bottom metal, adhesion to the cap layer greatly increased. The TiW/Ti/Au contact shows a contact resistivity of 450 Ω-μm² which is on the same order as the control. The Mo/Ti/Au contact shows a slightly better contact resistivity of 414 Ω-μm². The measured TLM resistances for the Mo/Ti/Au, TiW/Ti/Au, Ti/Pt/Au, and control contacts are shown in Fig. 2.

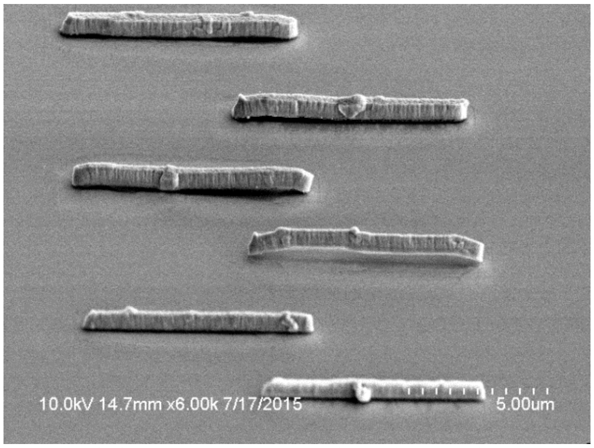

Fig. 3. Ti/Pt/Au emitters after annealing, showing clear signs of deformation and some have partially lifted off.

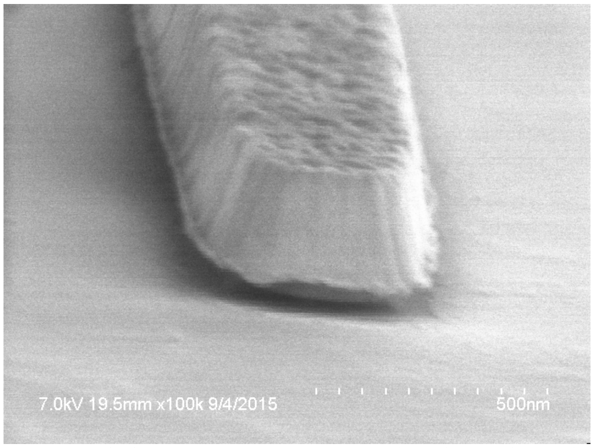

Fig. 4. Mo/Ti/Au emitters after emitter etch and annealing. The emitter shows very good adhesion and no evidence of e-beam resist pullback.

SEM of the Ti/Pt/Au annealed emitters show clear deformation and partial liftoff as shown in Fig. 3. In contrast, the Mo/Ti/Au and TiW/Ti/Au emitters retained their shape very well. Because a very thin film of metal was used in both cases, no significant e-beam resist pullback was observed. Fig. 4 shows a Mo/Ti/Au emitter after emitter etch and annealing.

CONCLUSIONS

Nonalloyed refractory contacts have been fabricated on an InP HBT substrate with an InAs/InGaAs emitter cap. Through TLM measurements, it was found that the inclusion of refractory metals (Mo, W, TiW) in the emitter contact effectively prevented metal diffusion into the semiconductor at elevated temperatures up to 420°C. Mo/Ti/Au and TiW/Ti/Au contacts showed similar room temperature contact resistivity values to Ti/Pt/Au, increasing to 414 Ω-μm² and of 450 Ω-μm² after annealing. Both contacts showed good emitter integrity even after a high temperature anneal, making them suitable for a self-aligned process.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
DHBT: Double Heterojunction Bipolar Transistor
f_T: Currrent gain cutoff frequency
f_{MAX}: Power gain cutoff frequency
PECVD: Plasma Enhanced Chemical Vapor Deposition
RIE: Reactive Ion Etching
TLM: Transfer Length Method / Transmission Line Measurement
SEM: Scanning Electron Microscope
SMU: Stimulus and Measurement Unit

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