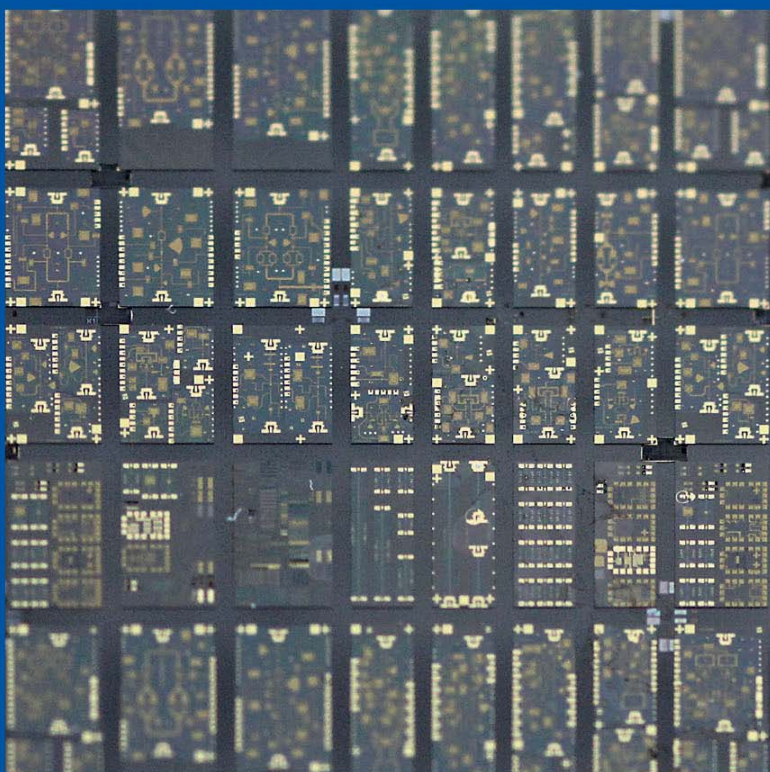
Leibniz Ferdinand Braun Institut

36

Innovationen mit Mikrowellen & Licht

Forschungsberichte aus dem
Ferdinand-Braun-Institut,
Leibniz-Institut
für Höchstfrequenztechnik

Indium phosphide HBT in thermally optimized periphery for applications up to 300 GHz



Ksenia Nosaeva

aus der Reihe:

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Indium phosphide HBT in thermally optimized periphery
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Innovations with Microwaves and Light

Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik

Preface of the Editors

Research-based ideas, developments, and concepts are the basis of scientific progress and competitiveness, expanding human knowledge and being expressed technologically as inventions. The resulting innovative products and services eventually find their way into public life.

Accordingly, the *"Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik"* series compile the institute's latest research and developments. We would like to make our results broadly accessible and to stimulate further discussions, not least to enable as many of our developments as possible to enhance everyday life.

The maximum frequencies and RF gain of indium phosphide (InP) bipolar transistors can be greatly enhanced by removing the native semiconductor substrate. The replacement with low-*k* dielectric material, however, leads to an increased thermal device resistance, which hinders high power operation. In this report, the monolithic integration of a nanocrystalline diamond heat spreading layer with InP bipolar transistor circuits intended for operation at 100 GHz and above is detailed. The addition of this diamond layer reported here reduced the InP transistor's thermal resistance by more than a factor of three, resulting in record thermal numbers for such devices.

We wish you an informative and inspiring reading

Prof. Dr. Günther Tränkle
Director

Prof. Dr.-Ing. Wolfgang Heinrich
Deputy Director

The Ferdinand-Braun-Institut

The Ferdinand-Braun-Institut researches electronic and optical components, modules and systems based on compound semiconductors. These devices are key enablers that address the needs of today's society in fields like communications, energy, health and mobility. Specifically, FBH develops light sources from the visible to the ultra-violet spectral range: high-power diode lasers with excellent beam quality, UV light sources and hybrid laser systems. Applications range from medical technology, high-precision metrology and sensors to optical communications in space. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter wave frontends targeting energy-efficient mobile communications as well as car safety systems. In addition, compact atmospheric microwave plasma sources that operate with economic low-voltage drivers are fabricated for use in a variety of applications, such as the treatment of skin diseases.

The FBH is a competence center for III-V compound semiconductors and has a strong international reputation. FBH competence covers the full range of capabilities, from design to fabrication to device characterization.

In close cooperation with industry, its research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. Thus, working in strategic partnerships with industry, FBH assures Germany's technological excellence in microwave and optoelectronic research.

Indium phosphide HBT in thermally optimized periphery for applications up to 300 GHz

vorgelegt von
M. Eng. and Tech.
Ksenia Nosaeva
Geb. in Topki, Kemerovo, Russische Föderation

Von der Fakultät IV - Elektrotechnik und Informatik -
der Technischen Universität Berlin
zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften
- Dr.-Ing. -

genehmigte Dissertation

Promotionsausschuss:

Vorsitzender: Prof. Dr. Tillack
Gutachter: Prof. Dr.-Ing. Heinrich
Gutachter: Prof. Dr. Tränkle
Gutachter: Prof. Dr.-Ing. Krozer (Universität Frankfurt am Main)

Tag der wissenschaftlichen Aussprache: 03 Juni 2016

Berlin 2016

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der
Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet
über http://dnb.d-nb.de abrufbar.
1. Aufl. - Göttingen: Cuvillier, 2016
Zugl.: (TU) Berlin, Univ., Diss., 2016

Nonnenstieg 8, 37075 Göttingen
Telefon: 0551-54724-0
Telefax: 0551-54724-21
www.cuvillier.de

1. Auflage, 2016
Gedruckt auf umweltfreundlichem, säurefreiem Papier aus nachhaltiger Forstwirtschaft.

ISBN 978-3-7369-9287-0
eISBN 978-3-7369-8287-1

Acknowledgment

“Art is I; science is we.”

Claude Bernard

I would like to thank many people for their help with my work. First of all, my supervisor Prof. Günter Tränkle, who is also a director of Ferdinand-Braun-Institute, where I spent these years writing my PhD thesis. The meetings with him were always constructive, funny and supportively. Many thanks to my second supervisor Dr. Nils Weimann. It is a person, who gave me advices, helped every day to solve numerous difficulties and problems during the processing time. He was always ready for help and valuable advices, and did it perfectly. I would like to thanks Dr. Matthias Rudolph for introduction into the world of thermal resistance extraction and circuit modelling, Steffen Schulz and Stefan Freyer for always quick measurements, Thualfiqar Al-Sawaf for circuit measurement results. Especially I’m grateful to my colleagues from the Process Technology department heading by Dr.Olaf Krüger. Thank you for the support in the process steps and nice time that we got together inside and outside of the clean room with Dirk Rentner, Steffen Hochheim, Matthias Matalla, Stefan Breuer, Natalia Sabelfeld, Natalia Kemf, Adrian Runge, Martin Thiemann and many others. And additionally I’m grateful to my colleagues from THz-Electronics group: Dimitri Stoppel, Sirinpa Monayakul und Ihab Schukfeh heading by Dr. Weimann for team work and nice time together.

Finally, thanks to my husband and my family for having inspired me

.

Zusammenfassung

Die Performance eines Transistors im Hochleistungsbetrieb wird durch thermische Effekte begrenzt. In dieser Doktorarbeit wird die Verbesserung des thermischen Managements von Indium Phosphid (InP) Doppel-Hetero-Bipolar-Transistoren (DHBTs), die mittels Transfer-Substrat-Prozesstechnologie (TS) hergestellt wurden, thematisiert. Durch den Transfer einer 10 µm dicken Diamantschicht auf die prozessierten InP DHBT und die Verwendung von Wärmebrücken durch die Diamantschicht kann prinzipiell eine Abnahme des Wärmewiederstands von mehr als 70% erreicht werden.

Die Verfügbarkeit von, mittels chemischer Gasphasenabscheidung (CVD) gewonnenen Diamantscheiben auf Silizium (Si)-Trägersubstraten macht es möglich, die Diamantschicht in den Stapel mit in BCB eingebetteten Transistoren, passiven Elementen und Metallverbindungen einzuführen. Dies geschieht durch ein Klebeverfahren und anschließender Entfernung des Si Träger-Substrats. Die vertikale thermische Verbindung zum Kollektor wird mittels induktiv gekoppelter Plasmaätzung durch die Diamant- und BCB-Schichten mit Sauerstoffplasma und ausschließender Galvanisierung realisiert.

Die elektrische Charakterisierung von Transistoren mit einem (1-Finger), zwei (2-Finger) und drei (3-Finger) Fingern nach Aufbringen der Diamantschicht zeigt eine Verbesserung des DC-Verhaltens und gleichzeitig keine Verschlechterung der HF-Eigenschaften des Bauteils. Die maximale Stromverstärkung ist dabei ähnlich dem des InP HBT, welcher in der Standard TS-Technologie ohne Diamant gefertigt wurde. Mit dem Diamant wurde eine Verringerung des Wärmewiderstands um 74% von 4.2 K/mW auf 1.1 K/mW beobachtet, die nach Kenntnis der Autorin der niedrigste Wärmewiderstand für 1-Finger InP HBTs mit $0.8\times5\ \mu m^2$ Emitterfläche ist. Für Mehrfinger-Transistoren sinkt der Wärmewiderstand ebenfalls von 4.1 K/mW auf 0.7 K/mW für 2-Finger- bzw. von 1.53 K/mW auf 0.54 K/mW für 3-Finger-Transistoren.

Die obere Grenze für den Kollektorstrom, der durch die Transistoren angesteuert werden konnte, erhöht sich mit einer Diamantschicht von 25 mA auf 30 mA für 1-Finger Transistoren, bzw. von 30 mA auf 50 mA für 2-Finger Transistoren, sowie von 35 mA auf 80 mA für 3-Finger HBTs. Bezüglich des Frequenzverhaltens wurde festgestellt, dass 2-Finger-Transistoren nach Diamant-Integration fast die gleichen Maximalfrequenzen wie 1-Finger HBT aufweisen. Dies deutet ebenfalls auf die Skalierbarkeit der Emitterfläche durch die verbesserte Wärmeableitung bei Verwendung von Diamant hin.

Die Transitfrequenz (f_t). (bzw. die Maximalfrequenz – f_{max}) erhöht sich ebenfalls, d.h. von 320 (285) GHz auf 340 (350) GHz für 1-Finger bzw. von 290 (250) GHz auf 360 (350) GHz für 2-Finger, sowie von 220 (150) GHz auf 305 (240) GHz für 3-Finger Transistoren.

Auf Basis der hier entwickelten Diamant-Wärmespreizer-Technologie wurden Leistungsverstärker entworfen, hergestellt und realisiert. Ein Design mit 2-Fach Kombinierung in der Ausgangstufe liefert eine maximale Ausgangsleistung von 20 dBm bei 5 dB Großsignalverstärkung und eine Power-added-efficiency (PAE) von 20%, eine Verbesserung der 4 dBm (mehr als einen Faktor von zwei) im Vergleich zu 16 dBm auf demselben InP HBT (vor dem Diamant-Transfer). Während innerhalb der Standardtechnologie ohne Diamant kein stabiler Betrieb eines Designs mit 4-Facher Kombinierung erreicht werden konnte, wurde dieser nach der Diamant-Wärmespreizer-Integration mit einer maximale Ausgangsleistung von 23 dBm bei einer PAE von 15% erreicht.

Abstract

The self-heating and thermal impedance limit indium phosphide (InP) HBT performances in scaled submicron technology. The improvement in thermal management of InP double heterojunction bipolar transistors (DHBTs) fabricated with transferred-substrate (TS) process is described in this thesis. By transferring a 10 μm thick chemically vapor deposited (CVD) diamond layer and establishing the heat bridges through the diamond, a decrease of thermal resistance in almost 4 times could be achieved.

The availability of nanocrystalline CVD diamond-on-silicon (Si) handle substrates makes it possible to introduce the diamond layer into the InP HBT MMIC stack with BCB-embedded transistors, passive elements and metal interconnects using the adhesive wafer-to-wafer bond process with subsequent removal of the Si host-substrate. Vertical thermal via connections through the diamond and BCB were created using inductively coupled plasma (ICP) etching with oxygen plasma and electroplating.

Electrical characterization of transistors after diamond transfer showed no degradation in RF characteristics and an improvement in DC behavior (collector current I_c increased capability). The maximum current gain was similar to the InP HBT standard TS technology without diamond. In doing so, a reduction in thermal resistance by 74% from 4.2 K/mW to 1.1 K/mW was observed, which to the autor's knowledge is the lowest thermal resistance for 1-finger InP HBTs with 0.8×5 μm^2 emitter area. Significant reduction of thermal resistance of multi-finger devices was achieved: from 4.1 K/mW down to 0.7 K/mW for double-finger HBTs and from 1.53 K/mW down to the recordly small 0.54 K/mW for three-finger devices. After diamond integration, 2-finger transistors showed almost the same maximum frequencies as their 1-finger counterparts, indicating the possible device area and hence device power scaling with the improved heat sinking, which could not previously be achieved without diamond.

The upper limit for the collector current, which could be driven through the transistors also increased from 25 mA to 30 mA for one-finger devices, from 30 mA to 50 mA for two-finger devices, and from 35 mA to 80 mA for three-finger devices. As a matter of fact, the improvement for 2-fingers and 3-fingers HBTs is more significant, because in this type of devices the thermal effects, those limiting device performances, are more pronounced due to devices layout (two, three metal lines – emitters – located near each other). The transition frequency and maximum oscillation frequency f_t/f_{max} were increased from 320/285 GHz to 340/350 GHz for a 1-finger device, from 290/250 GHz to 360/350 GHz for a 2-finger transistor, and from 220/150 GHz to 305/240 GHz for 3-finger device.

Based on the here developed diamond heat spreader technology, a medium-power amplifier (MPA) and a high-power amplifier (HPA) were designed, fabricated and realized. The MPA delivers a maximum output power of 20 dBm with 5 dB large-signal gain and a PAE of 20% representing the improvement of 4 dBm (more than a factor of two) compared to the 16 dBm measured before on the same device in the standard InP HBT technology without diamond. Within this technology, a stable operation of the high power amplifier could not be achieved. After a diamond heat spreader transfer, a maximum output power of 23 dBm at a PAE of 15% was reached.

Contents

1 Introduction

1.1 Motivation

We are currently living in an era of a rapidly developing technology. As a matter of fact, devices have to be faster, i.e. able to work in the higher frequency range. There is a demand for integrated circuits at frequencies up to 300 GHz and even higher for satellite communication, radars, spectroscopy, and imaging.

To realize the circuits for millimeter-wave and submillimeter-waves, the technology for fabricating the power amplifiers (PA), low-noise amplifiers (LNA), voltage controlled oscillators (VCO) and passive components have to be developed and established at a reasonable price. Therefore, the development of terahertz monolithic integrated circuits (TMICs) will revolutionize circuits and systems in the frequency band from 0.3 to 3 THz. It will enable the widespread adoption of new applications including active imagers and sensor arrays, where compact monolithically integrated circuits are the key to realizing the required element spacing and dense functionality [1].

Recent technological advances of InP-based devices have pushed the transistors bandwidth towards and even beyond 1 THz.

Indium Phosphide (InP) high-electron-mobility transistors (HEMTs) have attained bandwidth >1.2 THz at 50 nm gate length [2]. InP heterobipolar transistors (HBTs) have attained bandwidth >1 THz with 250 nm emitter length and lower [3], [4], [5]. The high f_{max} of these devices could be achieved due to high electron velocity in the InP material. Another advantage is a high bandgap, that leads to the breakdown voltage >4 V for InP-based devices. However, HBTs have key advantages over InP HEMT that enable complex MMICs. Given their high breakdown voltage, high digital speed, InP HBTs provide a platform in which all receiver and transmit components (LNA, VCO, and mixer) can be constructed. Single-chip construction eliminates THz waveguide connections between circuit blocks. This greatly reduces package size and interconnecting losses that currently limit the performances of THz blocks.

Silicon-germanium (SiGe) HBTs in bipolar complementary metal oxide semiconductor (BiCMOS) technology are also able to work with f_{max}>200-300 GHz. Each of the high frequency technologies mentioned above have advantages and shortcomings depending on the targeted application. Due to their unique material properties, InP-based devices have a higher breakdown voltage (>4 V) than BiCMOS devises based on Si, but lower or comparable with GaN RF HEMTS (3-18 V), as can be seen from Table