公開

研 究 終 了 報 告 書

「分極場工学による界面フォノン輸送の最適化」

研究期間： 2019 年 10 月～2023 年 3 月
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1. 研究のねらい

The aim of this research is to achieve the effective thermal management in the AlGaN/GaN high electron mobility transistors (HEMTs) for their application under high-power operations. The wide-bandgap semiconductor GaN is becoming the promising choice for power electronics to enable the roadmap of increasing power density by simultaneous high-power conversion efficiency and low form factor due to its superior characteristics of high breakdown voltages (10 times higher than Si), high switching speed (over GHz), and compact in size (reduced up to 1/1000 than Si power device). With the increased power density, self-heating inside the devices becomes an important issue for the failure and poor reliability in the real application. Unlike the conventional field effect transistor (FETs) which use impurity doping to produce n-type and p-type channels, the conducting n-channel in AlGaN/GaN HEMT is generated by the high-density two-dimensional electron gas (2DEG) at the heterojunctions, leading to the localized hotspots at the gate edge close to the drain site. The considerable power dissipation, which is more than 10 times higher than Si transistors, has been observed. Nevertheless, as a result of the poor physical understanding of the phonon transport in the nanometer scale, there is **NO** effective thermal management strategy to dissipate the so high-level powers. Different from Si transistors, the thermal boundary resistance (TBR) as high as ~47.6 m^2K/GW between GaN and their heat spreader (typically, diamond) was observed due to interface scattering, vacancy/impurity scattering, ground boundaries or interface disorder/roughness. Therefore, an effective thermal dissipation strategy from GaN to heat spreader is in urgent demand to improve the power dissipation of GaN HETMs.

In this project, we propose to deposit polycrystalline diamond film with a high thermal conductivity directly at the hot spots to enhance the thermal dissipation of AlGaN/GaN HEMTs. The TBR is greatly reduced by using nanodiamond seeding before the deposition of diamond film with microwave plasma chemical vapor deposition (MPCVD). To physically understand the thermal transport behavior at the interface, the nanoelectromechanical or microelectromechanical systems (NEMS/MEMS) are proposed for phonon behavior analysis.

2. 研究成果

(1) 概要
1) To investigate the phonon transport at the heterojunction of GaN/AlN, the double-clamped MEMS bridge was fabricated. It was found that the strain at the interface can greatly enhance the quality factor and improve the frequency stability. The heterojunction resonator showed a much higher thermal stability compared to the Si-based resonators.

2) Highly orientated polycrystalline diamond film was deposited on GaN template by micro-plasma chemical vapor deposition. Nanodiamonds was proposed as the seeds. The diamond film has a thermal conductivity approaching 250W/mK when the thickness is ~1 um, belonging to the high level for polycrystalline diamond film. With nanodiamond seeding, the thermal boundary resistance was estimated to be $7m^2K/GW$ between diamond film and GaN, which is much lower than those with SiNx of AlN interlayers.
3) From simulation, the phonon transportation from GaN to diamond was investigated with respect to different scattering and piezoelectric field. It was found that, the interface roughness greatly influences the high-frequency phonon transportation.

(2)詳細

Research Theme 1: Thermal transportation through MEMS structure

The MEMS structure was utilized based on the GaN/AlN heterojunction to investigate the phonon behavior at the strained interface. The double-clamped bridge MEMS resonator was fabricated using the nanofabrication process. The resonance frequency measurement was performed with a laser doppler technique. The temperature dependent quality factor and resonance frequency were analyzed. At the GaN/AlN heterojunction, due to the lattice mismatch, a large strain induced piezoelectric field dominated the resonance behaviors. It was found that, the piezoelectric field greatly increased the quality factor of the resonator (as demonstrated in Ref.1).[1)] A value of more than 10^6 was obtained, which is the **highest value** ever reported for the GaN-based resonator.[1)] It was also found that, the strain induced piezoelectric field could improve the frequency stability of the resonator when the temperature was changed. A temperature coefficient of frequency (TCF) of ~ -5 ppm/K was obtained, which is much lower than those of Si-based resonators, as shown in Table1. The detailed results were reported in Ref.2.[2)] This achievement is very promising for the timing devices toward the 5G application.

The above achievements were accepted by the 66th International Electron device Meeting (IEDM 2020), whose acceptance ratio is lower than 30%. We also have a **press release** based on the above achievements from JST：https://www.jst.go.jp/pr/info/info1474/index.html.

Table 1 Comparison of the TCF for resonators fabricated from different materials

Materials	Si	GaN	GaN	GaN	AlN	AlN	SiC	**GaN/Si**
TCF (ppm/K)	-30	-17.7	-22.8	-15	-35	-106	-22	**-3-13**
Q	650 000	1300	2000	720	1283	1868	13000	**120 000**
T (K)	383	353	423	300	300	358	333	**600**
Reference	Bourgeois, et al. IFCS, 1997	Gokhale, et al. Transducers 2011	Ji, et al. CPB, 2019	Ansari, et al. EDL, 2014	Hui, et al. EFTF/IFC, 2013	Yang, et al. Micromachines. 2019	Chang, et al. Sensor, 2008	**This work**

Research Theme 2: Diamond deposition on GaN with nanodiamond seeds for the effective thermal dissipation

Diamond has the highest thermal conductivity among any known materials, and is utilized as the effective heat spreader for HEMTs. However, diamond and GaN have a large acoustic mismatch (>11%), leading to a large TBR at the interface. Here, we propose to directly deposit highly orientated polycrystalline diamond (PCD) film on GaN template for the thermal dissipation directly from hot spots. Nanodiamonds was proposed as the seeds. From Raman spectrum, the strong diamond peak was observed, indicating the successful growth. It was found that, the polycrystalline diamond was obtained even without SiNx as protection layer. With only nanodiamond seeds, the quality of diamond was good. SEM also indicated the highly oriented behavior of diamond film. The thermal conductivity of diamond film is increased with the grain size of diamond increasing. A high value approaching 250 W/mK was obtained when the grain size is larger than 1500 nm, which belongs to the high level for polycrystalline diamond film. Then the effective TBR was measured between GaN and diamond. A low value of 4m^{2}K/GW was obtained when AlN/GaN superlattices was utilized as interlayer, which is much lower than those with SiNx of AlN interlayers (Fig. 1). This result shows the nanodiamonds with a high thermal conductivity can replace SiNx with the low thermal conductivity as the seeds and protection layer for diamond growth. With the superlattices interlayer with piezoelectric field, the TBR was greatly reduced.

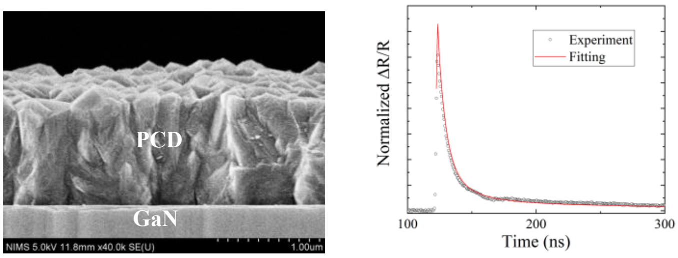

Fig. 1 Cross-sectional SEM showing the polycrystalline diamond grown on GaN template; TDTR signal and fitting result for GaN/diamond.

References:

1. Liwen Sang*, Meiyong Liao, Xuelin Yang, Huanying Sun, Jie Zhang, Masatomo Sumiya, Bo Shen. Strain-enhanced high Q-factor GaN micro-electromechanical resonator. Science and Technology of Advanced Materials. 21 [1] (2020) 515-523 10.1080/14686996.2020.1792257

2. Liwen Sang, Huanying Sun, Xuelin Yang, Tiefu Li, Bo Shen, and Meiyong Liao, Self-Temperature-Compensated GaN MEMS Resonators through Strain Engineering up to 600 K, IEDM 2020.

3. 今後の展開

In future, the developed strategy will be utilized to the high-power and RF electronic devices. The method by using nanodiamond seeds to deposit PCD obtained outside research interest and the collaborations are under discussion.

4. 自己評価

In the purpose, we aim to develop an effective thermal management architecture for GaN HEMTs to achieve the cooling limit between GaN and diamond. From DMM model estimation, the ideal TBR between GaN and diamond is ~ 3 m^{2}K/GW. Finally, we have obtained the TBR ~ 4

m^2K/GW between GaN and diamond. The physical mechanism was clarified with theoretical calculation and MEMS/NEMS analysis. The collaboration with company on GaN-on-diamond is expected. The progress works well according to the research plan of the project.

5. 主な研究成果リスト

(1)代表的な論文(原著論文)発表

研究期間累積件数:32件

1. **Liwen Sang***, Diamond as the heat spreader for the thermal dissipation of GaN-based electronic devices, Functional Diamond, 2021, 1, 174-188
This is a review article on the thermal dissipation strategy of GaN electronic devices.
2. **Liwen Sang**, Huanying Sun, Xuelin Yang, Tiefu Li, Bo Shen, and Meiyong Liao, Self-Temperature-Compensated GaN MEMS Resonators through Strain Engineering up to 600 K, IEDM 2020.
In this paper, we demonstrated a novel self-temperature-compensated strategy for GaN-based MEMS resonator with an ultra-low temperature coefficient of frequency without losing the quality factor up to 600 K. This work utilized the elastic strain to engineering the phonon transportation and the thermal stress compensation was realized.
3. サン リウエン*, 廖 梅勇. GaN 基板上ダイヤモンド膜の成長と放熱性向上. New diamond. (2022) 25-27
In this paper, high quality polycrystalline diamond film with a high thermal conductivity is successfully deposited on GaN with nanodiamond seeds.

(2)特許出願

研究期間全出願件数:1 件(特許公開前のものも含む)

(3)その他の成果(主要な学会発表、受賞、著作物、プレスリリース等)

(受賞)

令和4年度 文部科学大臣若手科学者賞

(学会発表)

1、Liwen Sang. Photoelectricity energy conversion devices based on III-V Nitride semiconductors. 3rd International Conference on MATERIAL SCIENCE & NANOTECHNOLOGY, ICMSN202, Invited.

(プレスリリース)

1、2020年12月14日、科学技術振興機構報、「窒化ガリウムでMEMS振動子を開発～5G通信向けの高集積発振器に期待～」 https://www.jst.go.jp/pr/info/info1474/index.html

2、2021年1月7日、電波新聞、「【2021 年注目の先端技術特集 】JSTが 窒化ガリウムでMEMS 振動子開発」、https://dempa-digital.com/article/151368

3、2020年12月15日、OPTRONICS、「NIMS，GaN で高性能 MEMS 振動子を開発」 https://optronics-media.com/news/20201215/70892/