窒化アルミニウム(AlN)を用いた高温デバイスの作製

Fabrication of extreme-temperature devices using Aluminum Nitride (AlN)

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概 要 / Overview

Si(シリコン、ケイ素)半導体は、あらゆる機器に使われており、私たちの生活に欠かせないものになっています。しかし、Si素子の動作可能温度は300℃以下に限られます。本研究では、900℃まで測定可能な電気特性の評価装置を用意し、優れた結晶品質を持つ独自のAlN試料を用いてダイオードとトランジスタの作製および評価を行い、ダイオードは827℃、トランジスタは727℃での動作に成功しました。低価格かつ大面積試料が入手可能なサファイア基板上AlN層を用いている点と、シンプルな構造の素子で耐熱性を実現した点で、実用性にも優れていると言えます。本研究成果により、800℃を超える厳環境での半導体素子利用が可能になりました。この技術は、高温環境であるために制限されていた地下開発や鉄鋼、宇宙・航空産業への貢献が期待されます。

Tsukuba, Japan—Silicon (Si) semiconductors are ubiquitous in electrical appliances and play an essential role in our daily lives. However, in high-temperature environments exceeding 300℃, such as underground resource drilling, space exploration, and engine peripherals, improved semiconductor materials are required because of the limited operational temperature range of Si devices. This study presents the fabrication and evaluation of high-quality AlN-layered diodes and transistors using a novel electrical characterization system capable of functioning at temperatures up to 900℃. The researchers achieved a successful demonstration of diode operation at 827℃, surpassing all previous records, and the transistors operated at 727℃. This research has paved the way for operable semiconductor devices to operate in severe environments (>800℃). These AlN devices are expected to be employed in high-temperature industries such as underground mining, steel production, space exploration, and aviation.

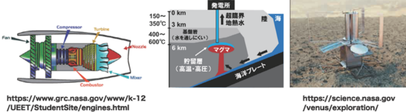
背景

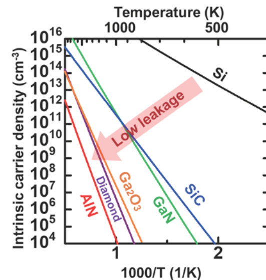
Introduction

● 高温デバイスの利用先とAlNの特徴

Applications

- Venus's exploration
- Jet engine, automotive
- Deep-well drilling





Aluminum nitride (AlN)

- ☺ Large high-quality templates
- ☺ Possible n-type and p-type doping
- ☺ Small intrinsic carrier density (n_i)
- ☹ High ionization energy of dopants

	Si	SiC	GaN	β-Ga_2O_3	Diamond	AlN
Bandgap energy (eV)	1.1	3.3	3.4	4.7	5.5	6.1
Carrier type	P☺/N☺	P☺/N☺	P☺/N☺	P☹/N☺	P☺/N☹	P☺/N☺
n_i (cm^{-3}) at 1000°C	>10^{16}	~10^{14}	~10^{14}	~10^{10}	~10^{9}	~10^{8}
Thermal conductivity (W/mK)	156	490	200	27	2000	290

実験方法

Experimental procedure

● 導電性AlN試料とダイオードの作製プロセス

AlN samples (DOWA electronics)

- Substrate : sapphire
- AlN layer : 3 μm, UID

Ion implantation

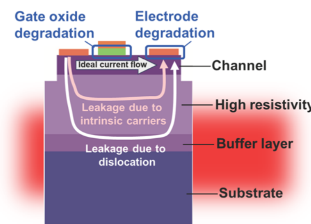
- Material : Si
- Energy : 90, 40, 10 keV
- Total dose : 5×10^{14} cm^{-2}
- Tilt angle : 7 degree

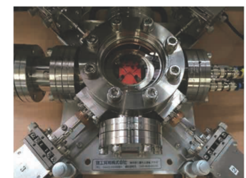
Thermal annealing

- Temperature : 1500℃
- Atmosphere : N_2

Device fabrication

- MESA : Cl_2-gas RIE
- Ohmic : Ti/Al/Ni/Au + Heated at 950℃
  Schottky : Ni/Au





High-temperature probe station
(< 900°C, ~10^{-5} Pa)

AlN層の電気的特性

Electrical characteristics of AlN layers

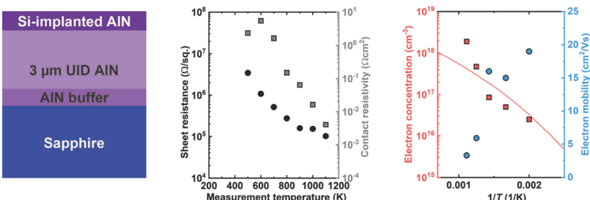
● 877℃でも安定な電極と材料

TLM measurement

- Reduction of ρ_c with increasing T_m due to enhanced TFE :
  4×10^{-3} Ωcm² at 1100K
- Reduction of R_s and n_e with increasing T_m due to enhanced donor ionization :
  100 kΩ/sq. at 1100K

Hall-effect measurement

- Reduction of μ_e with increasing T_m due to phonon scattering :
  19 cm²/Ks at 500K, 3 cm²/Ks at 900K
- T_m dependent Hall effect :
  E_d=320 meV, corresponding to DX^- center ($2d^0 \Leftrightarrow d^+ + DX^-$)
  N_d=2×10^{18} cm^{-3}, N_a=1×10^{17} cm^{-3}, indicating donor activation (N_d/[Si]) ratio of 10%



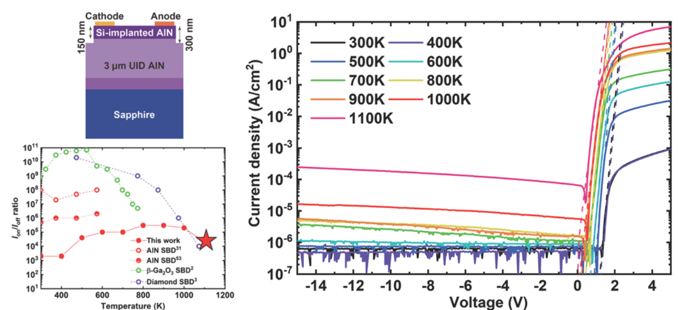
H. Okumura, Y. Watanabe, and T. Shibata, Applied Physics Express, 16, 064005 (2023).

AlNショットキー接合ダイオード

AlN Schottky barrier diodes

● 世界最高温度(827℃)でのダイオードの動作実証に成功！

- Reduction of V_{on} with increasing T_m due to shrunk E_g : 1.47 V at 500K, 1.16 V at 1000K
- Reduction of R_{on} with increasing T_m due to increased n_e and decreased ρ_c :
  3.8×10^{3} Ωcm² at 300 K, 4.2×10^{-1} Ωcm² at 1100 K
- Increase of I_{max} at 3 V with increasing T_m : 3.9×10^{-4} A/cm² at 300 K, 3.6 A/cm² at 1100 K
- On/off ratio : ~10^{4} at 1100 K
- Breakdown voltage : 610 V at 300 K



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