Fabrication and Testing of Gallium Nitride Transistors

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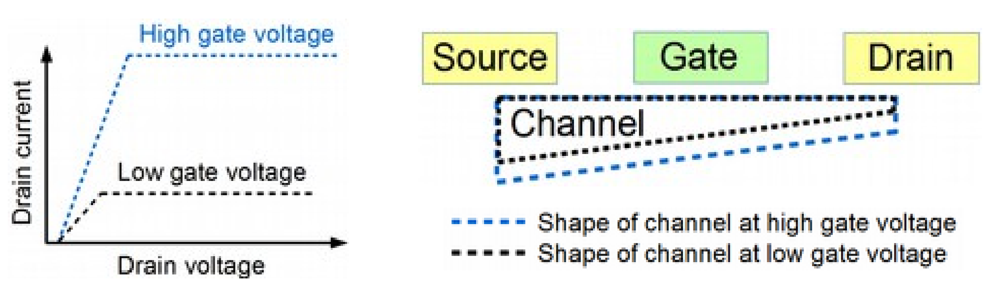
How Transistors Work

Transistors are devices used for switching and amplifying. The "field effect transistor" has 3 terminals called the source, drain, and gate.

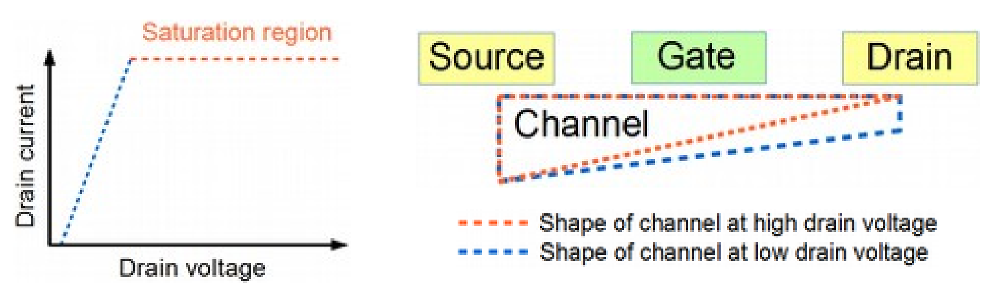
Current flows from drain to source through a conducting channel underneath the terminals. A voltage applied at the drain causes current to flow.

The gate controls how conductive the channel is by using a positive voltage to attract electrons to the channel.



The thickness and conductivity of the channel depends on the voltage difference between the gate and the channel. This difference is smallest where the drain voltage is applied. Hence, the channel is thinnest at the drain end.

If a large enough drain voltage is applied, the channel becomes "pinched off". This means current is still able to flow from drain to source, but further increases in drain voltage have little effect on the current.

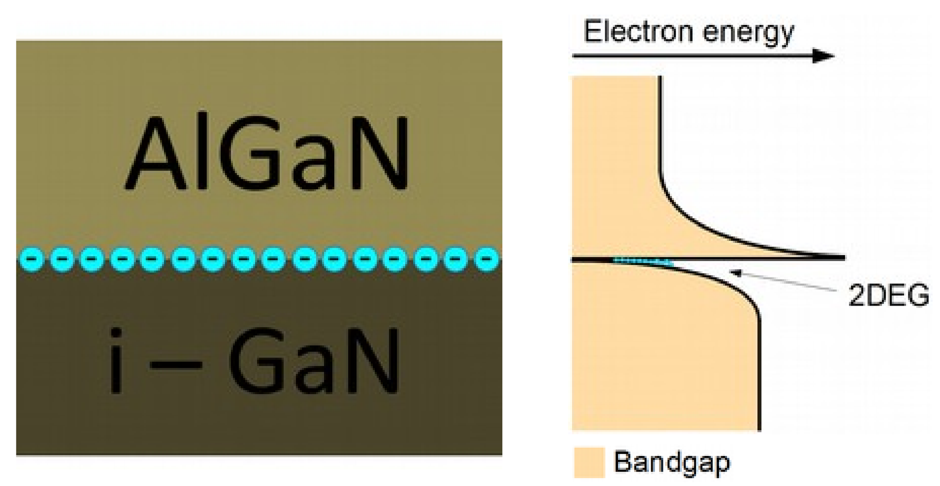


Ideally, the incremental resistance in the saturation region should be infinite (i.e the curve should be flat) because this results in higher-gain amplifiers. In reality though, the curve often slopes upward due to channel length modulation, or downward due to decreasing electron mobility.

High Electron Mobility

In GaN transistors, current flows through a 2-dimensional electron gas (2DEG), which has a high concentration of high mobility electrons[7]. Hence, they are classified as High Electron Mobility Transistors (HEMTs).

The 2DEG is formed by an energy well at the junction of a GaN and AlGaN layer. Because the well is very thin, movement of electrons is restricted to 2 dimensions[7].



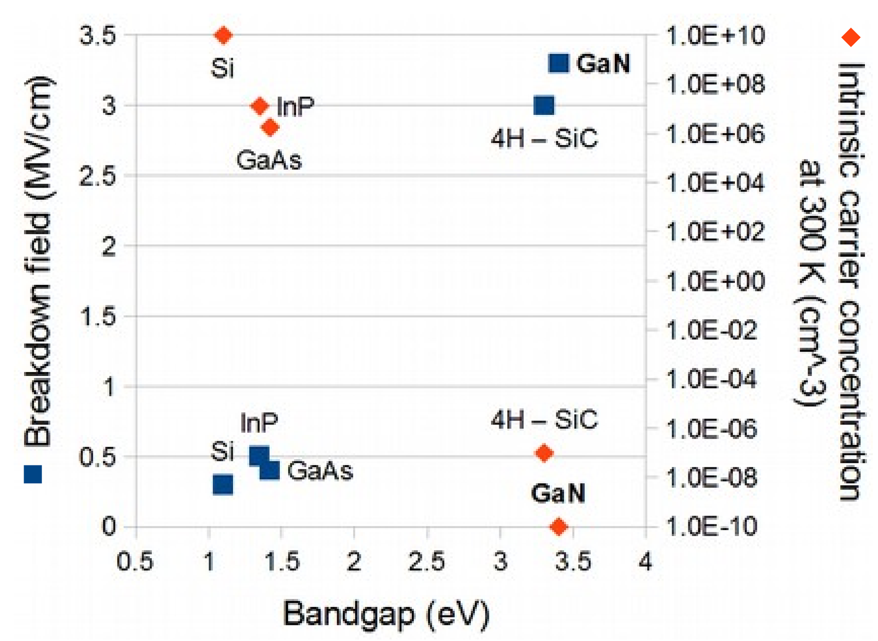
i-GaN stands for "intrinsic" GaN, which means the GaN is undoped (does not contain impurities).

Wide Bandgap Advantage

The bandgap is the energy required for a bound valence electron to become free. GaN has a wide bandgap which:

- Increases the breakdown field, which is the strongest electric field the transistor can withstand
- Decreases the number of intrinsic carriers, which are the electrons and holes in an intrinsic material that conduct current

Maximum operating voltage is proportional to breakdown field. Maximum operating temperature is inversely related to intrinsic carrier concentration.



Data obtained from [1], [8], [9], [10]

Fabrication Techniques

To form the components of a transistor, metals must be added to and removed from specific areas of the substrate. This is done with the help of photoresist.

Photoresist is a chemical that dissolves easily in a solution called "developer", if it is exposed to UV light beforehand. The first step is to coat the entire sample with photoresist.

A photomask is like a stencil that is placed over the photoresist during UV light exposure. Only the photoresist exposed to UV light dissolves in the developer solution. This leaves some areas of the sample free of photoresist.

Step	Subtractive	Lift-off
1	Deposit photoresist	Deposit photoresist
2	Align photomask	Align photomask
3	Expose to UV light	Expose to UV light
4	Immerse in developer solution	Immerse in developer solution
5	Remove metal from photoresist-free regions	Deposit metal everywhere
6	Immerse in acetone to remove undeveloped photoresist	Immerse in acetone to remove undeveloped photoresist and metal

Step	Ni/Au or Cr/Au deposition
1	Deposit photoresist
2	Deposit aluminium
3	Deposit photoresist
4	Align photomask
5	Expose to UV light
6	Immerse in developer solution
7	Remove aluminium from photoresist-free regions
8	Expose to UV light without photomask
9	Immerse in developer solution
10	Deposit Ni/Au or Cr/Au everywhere
11	Immerse in acetone to remove undeveloped photoresist and metal

Subtractive process: When the sample is immersed in a metal-etching chemical, only the photoresist-free areas will be affected. Acetone then washes away the undeveloped photoresist.

Lift-off process: After photoresist development, metal is deposited on the entire sample. When immersed in acetone, the metal on photoresist-free regions stays on the sample. Metal everywhere else is lifted off as the photoresist is washed away.

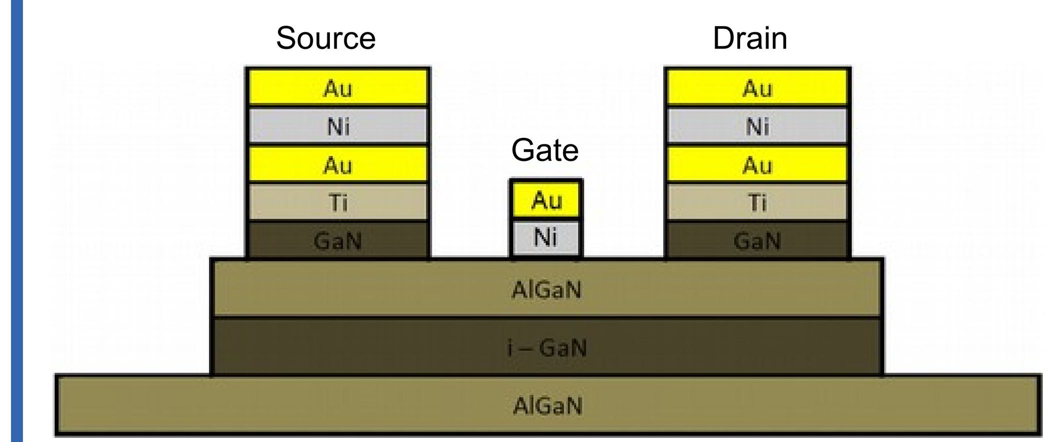
The subtractive process was used to etch Ti and Au. To deposit Ni/Au and Cr/Au we had to use a combination of the subtractive and lift-off processes.

Final Transistor Structure

- Au prevents oxidation of the lower layers.
- Ni and Cr both form good Schottky contacts with AlGaN.
- Titanium forms a good ohmic contact with GaN.
- The GaN immediately below the Ti lowers contact resistance by allowing electrons to tunnel more easily.
- The 2DEG exists at the AlGaN / i – GaN junction.

Ohmic contacts allow current to flow in both directions.

Schottky contacts allow current to flow only from metal (Ni or Cr) to semiconductor (AlGaN).



Cross section of the Ni samples. Cr samples had Cr substituted in place of Ni.

Benefits of Gallium Nitride

Gallium nitride (GaN) based transistors can be operated at higher voltages, temperatures, and frequencies compared to silicon-based transistors[1] [2]. However, the high fabrication cost limits them to niche applications such as:

- amplification for cellphone base stations[1]
- handheld radio devices for the military[2]
- radar[2]
- satellite communication[2]
- power converters for solar cells[3]
- automotive electronics[4]
- deep-well drill sensors for petroleum exploration[4]

Property	Benefits
Wide bandgap (more energy is required to free valence electrons)	• Works at high temperatures[4] • High breakdown field[1] ○ High operating voltage[1] ○ High power density[1] ○ Low power loss[5]
2-dimensional electron gas	• High electron velocity[6] ○ High frequency[6]

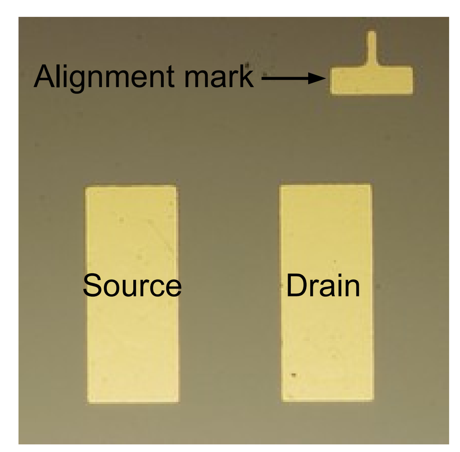
How we tested our samples

We made 5 samples. Samples 1, 2, and 3 had nickel/gold (Ni/Au) gates and Samples 4 and 5 had chromium/gold (Cr/Au) gates.

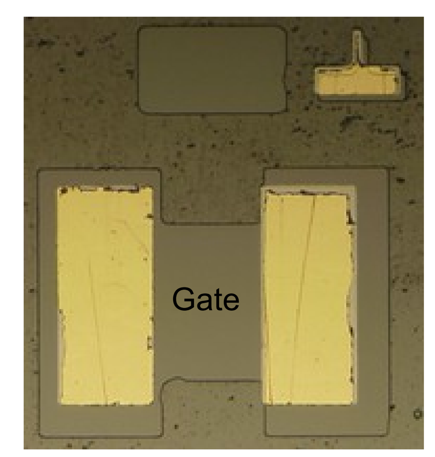
Each sample had 48 transistors arranged in 6 rows and 8 columns. Transistors were named by assigning a letter to each row and a number to each column.

We annealed (heated) the samples for 2 minutes at temperatures ranging from 350 to 600 Celcius. We also performed breakdown voltage tests.

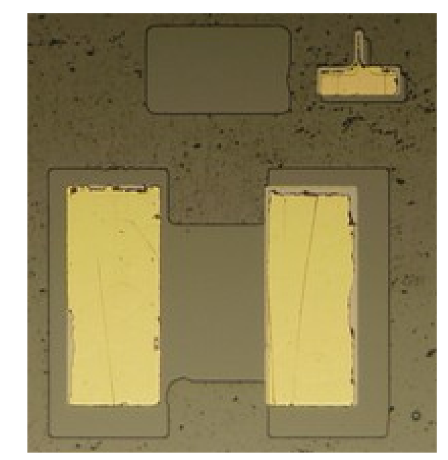
Photos of the Fabrication Process



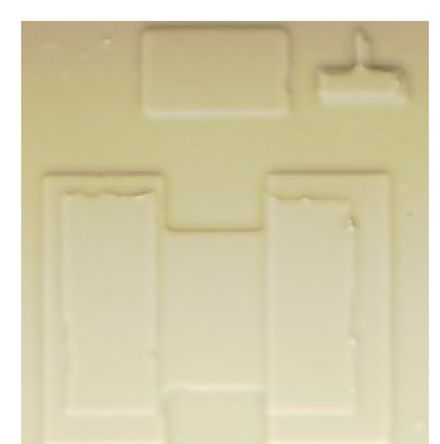
1. Etch Ti and Au everywhere, excluding source, drain, and alignment mark.



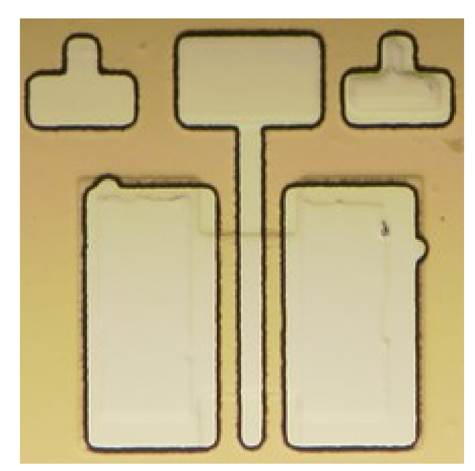
2. Use reactive ion etching to remove GaN cap and AlGaN everywhere, excluding source, drain, and gate.



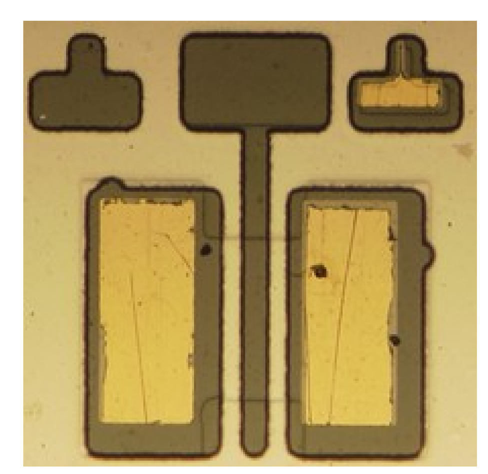
3. Etch GaN cap from gate.



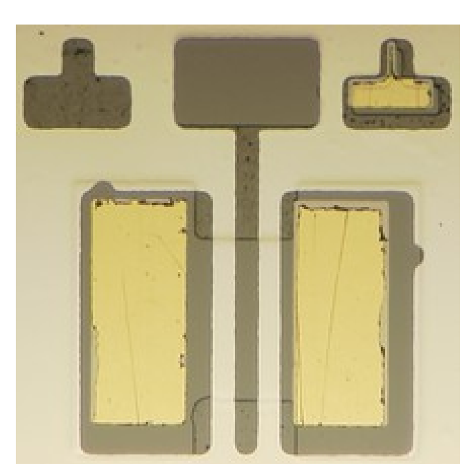
4. Deposit aluminium everywhere on top of the photoresist.



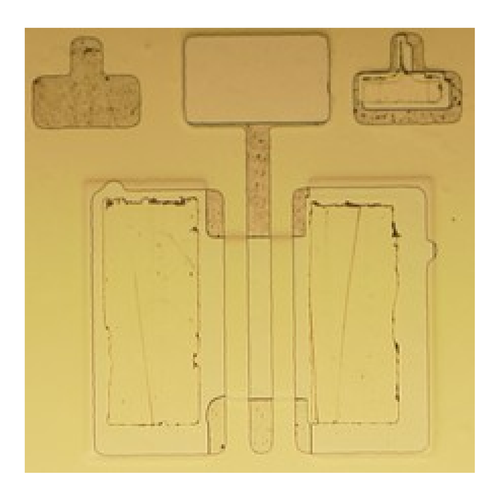
5. After depositing photoresist, exposing to UV light, and immersing in developer solution, the white areas are free of photoresist.



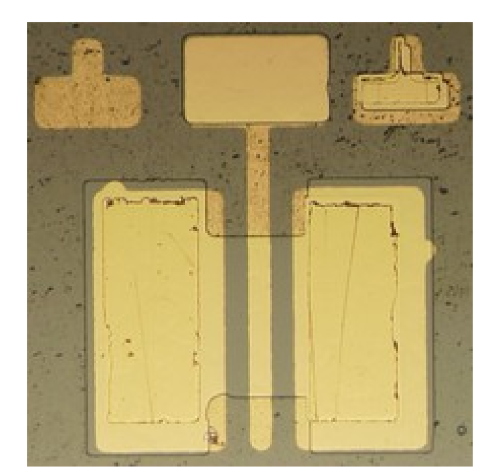
6. After the aluminium is etched, the gold layer is visible.



7. After immersing in developer solution, the entire surface is free of photoresist.

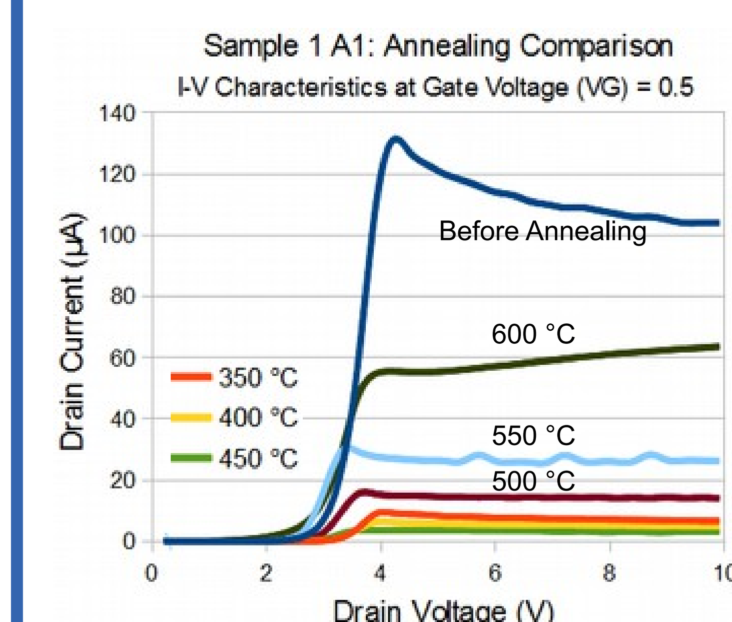


8. Deposit chromium and then gold everywhere.

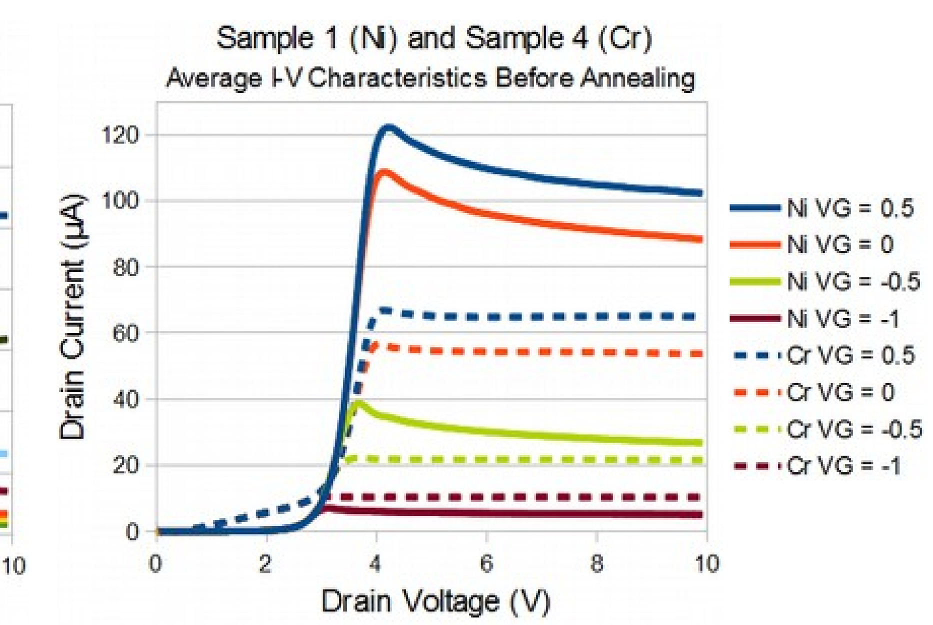


9. Remove Al/Cr/Au everywhere, excluding source, drain, and gate.

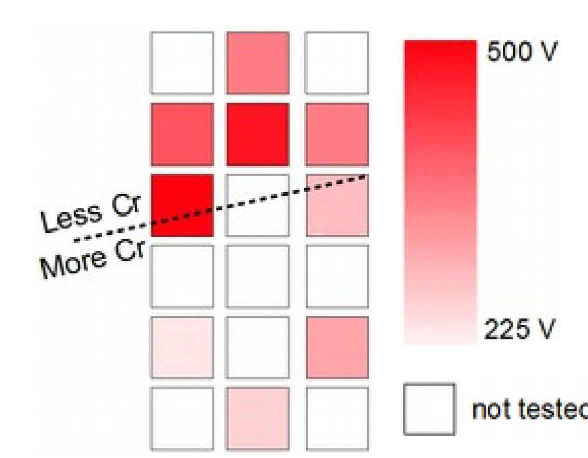
Annealing and Breakdown Results



The graph above shows one current-voltage (I-V) curve of an Ni sample, before and after annealing at various temperatures. Annealing at 350-450 °C tends to flatten the saturation region, but cause a significant drop in current. Beyond 450 °C current increases again.



The graph above shows the average I-V curves of 23 Ni devices and 22 Cr devices, all before annealing. At gate voltages greater than -1 V, each Cr curve had lower current than the corresponding nickel curve (shown in the same color). The Cr samples had flat saturation regions, prior to being annealed, whereas the Ni samples developed flat saturation regions only after being annealed.



Above, the array of squares represents transistors and their physical location on sample 5. This sample had a non-uniform distribution of chromium. The intensity of red indicates the breakdown voltage of each transistor. On this sample, breakdown voltage seemed to be inversely related to chromium thickness. Most transistors on the other samples were more resilient and broke down when 400-500 V was applied.

Acknowledgements

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