

# 2DEG-HEATED AlGaIn/GaN MICRO-HOTPLATES FOR HIGH-TEMPERATURE CHEMICAL SENSING MICROSYSTEMS

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## ABSTRACT

Fully-suspended AlGaIn/GaN micro-hotplates that leverage self-heating of the two-dimensional electron gas (2DEG) have been modeled, micro-fabricated, and characterized at elevated ambient temperatures (from 25°C to 600°C in air). An input power of ~75 mW heated the micro-hotplates to approximately 270°C from 25°C ambient conditions. In addition, finite element analysis (FEA) showed high-temperature uniformity across the micro-hotplate (<1% variation) and fast transient response times (~2 ms rise and fall times). These results support the use of the AlGaIn/GaN-on-Si platform for high-temperature activation of chemical sensing catalysts and in-situ chemical sensing within high-temperature environments (e.g., combustion exhaust, industrial process, and downhole).

## INTRODUCTION

The global market of chemical sensors is forecasted to reach about 31 billion US dollars by 2020 [1]. Data collected by chemical sensors can aid in emission control, energy savings, environmental monitoring, and catastrophe prevention [2-5]. For chemical sensing, a functional sensing layer (catalyst) transduces the chemical signals into electrical signals, which are then detected by the underlying sensor platform. To ensure reliable signals and reduced baseline drift, the sensing layer needs to be regenerated (burned off) periodically at elevated temperatures. In addition, many functional sensing materials exhibit increased sensitivity at elevated temperatures. For example, ZnO nanorods demonstrated enhanced sensitivity to hydrogen at approximately 250°C [6]. To sustain elevated temperatures during operation, a heating element is often integrated into the sensor system. Micro-hotplates, which are suspended and thermally isolated (reduced power consumption) structures with embedded heaters, are often utilized.

Commonly used micro-hotplates are composed of silicon oxide/nitride membranes and metallic heaters. Such systems suffer from reliability issues caused by electro-migration of metal atoms [7]. In addition, localized stress and voids in metal traces often lead to premature rupture of the membranes and drift of the heating characteristics [7]. In addition, micro-hotplates with metal heaters often employ complex heater geometries to achieve uniform temperature distribution [8]. Thus, micro-hotplates made from doped semiconductor materials (e.g., Si and SiC) have been used to mitigate the reliability issues caused by metal electro-migration. Additionally, as the semiconductor plate itself serves as the heater, such micro-hotplates can produce uniform temperature distributions using simple layout geometries. For high-temperature chemical sensing (> 300°C), self-heated silicon carbide (SiC) micro-hotplates have been developed, but custom substrates and advanced membrane release chemistry are required [9], which makes integration with electronics challenging.

In contrast, the self-heated AlGaIn/GaN micro-hotplates reported here utilize commercial AlGaIn/GaN-on-Si wafers and a common Si release process (XeF<sub>2</sub>), which supports monolithic integration with GaN electronics and high-temperature operation. Monolithic GaN-based microsystems are appealing for sensing applications in harsh environments, such as combustion exhaust

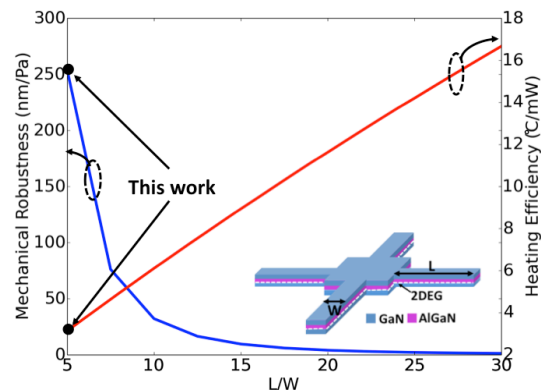


Figure 1: The influence of heater arm geometry on heating efficiency and mechanical robustness (out-of-plane displacement per unit perpendicularly applied pressure) of four-arm micro-hotplates studied by analytical modeling and FEA.

pipes, industrial manufacturing processes, and oil & gas wellbores, due to the inherent temperature- and chemical-tolerance of GaN. AlGaIn/GaN heterostructures have been commercialized for high-frequency and high-power electronics thanks to the highly conductive two-dimensional electron gas (2DEG) at the AlGaIn/GaN interface [10]. In addition, the 2DEG is sensitive to surface charges and thus can be used for chemical sensing applications [11-12]. Moreover, due to the wide bandgap of GaN, AlGaIn/GaN devices have demonstrated successful operation up to 600°C [13]. Furthermore, GaN energy harvesters and resonators [14-15] leveraging the piezoelectric properties of GaN can also be integrated on a single chip to make self-powered wireless sensing nodes. This paper presents the modeling, micro-fabrication, and characterization (interpolation-based) of the first 2DEG-heated AlGaIn/GaN micro-hotplate architecture reported in the literature. In addition, uncertainty analysis of the characterization method and future work are discussed.

## DESIGN AND MODELING

Analytical modeling and finite element analysis (FEA) were used to predict the effect of micro-hotplate geometry on heating efficiency (maximum temperature rise per unit input power) and mechanical robustness (maximum out-of-plane displacement per unit perpendicularly applied pressure) (Fig. 1). The results reveal that increasing the ratio of the heater arm length (L) to width (W) can enhance the heating efficiency but reduces the mechanical robustness of the micro-hotplate. It should be noted that the mechanical robustness falls at a much faster rate than the heating efficiency improves. To ensure that the micro-hotplate has sufficient mechanical robustness,  $L/W = 5$  was chosen for this work ( $L = 100 \mu\text{m}$  and  $W = 20 \mu\text{m}$ ). For this work, a spiral four-arm layout was chosen due to the fact that given the same L/W, a spiral four-arm micro-hotplate (Fig. 2a) spans a much smaller area than a conventional four-arm design (schematic shown in the inset of Fig. 1) while maintaining a similar heating efficiency and mechanical robustness. To ensure reliable operation, the thermal stress in the spiral four-arm micro-hotplate

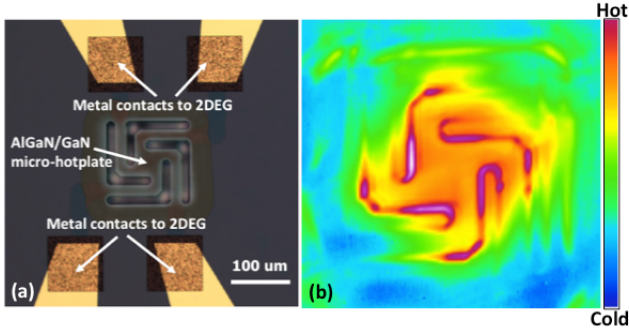


Figure 2: Optical image of a microfabricated AlGaIn/GaN micro-hotplates (a), and infrared (IR) image of a micro-hotplate showing the temperature profile during operation (b).

Table 1. Material properties used in FEA.

Thermal conductivity	130 W/(m-K) [16]
Electrical conductivity	815 S/m for design phase; Temperature dependent for micro-hotplate characterization
Young's modulus	300 GPa [17]
Poisson's ratio	0.23 [18]
Coefficient of thermal expansion (CTE)	Temperature dependent [19]
Heat capacity	491 J/(kg-K) [16]
Density	$6.15 \times 10^3$ kg/m <sup>3</sup> [20]

should be smaller than the yield stress of the GaN membrane. For the geometry of  $L = 100 \mu\text{m}$  and  $W = 20 \mu\text{m}$ , the maximum von Mises computed by FEA was approximately 630 MPa when the plate is heated to 330°C (ambient temperature at 25°C). This is lower than the yield stress of GaN at that temperature ( $> 1000$  MPa) [21]. The maximum stress occurs at the intersection of the plate and the heater arms.

Detailed FEA (COMSOL Multiphysics®) of the spiral four-arm AlGaIn/GaN micro-hotplate was conducted taking into account the nominal microfabricated geometry (GaN membrane thickness = 3  $\mu\text{m}$ , heater arm length = 100  $\mu\text{m}$ , heater arm width = 20  $\mu\text{m}$ , and central plate size = 50  $\mu\text{m}$  by 50  $\mu\text{m}$ ). In addition, the temperature-dependent properties (electrical conductivity of 2DEG and coefficient of thermal expansion) were utilized. The material properties of the micro-hotplates modeled in FEA are summarized in Table 1. Using these properties, the temperature profiles of the micro-hotplate (nominal geometry) were computed and the temperature profiles were visualized. The FEA results showed very high temperature uniformity across the main plate ( $\sim 1\%$  variation) in agreement with the infrared (IR) images taken during operation Fig. 2b. In addition, the FEA transient simulation results (Fig. 3) reveal that the micro-hotplate has fast heating (rise) and cooling (fall) transient response times ( $\sim 2$  ms).

## MICROFABRICATION

The micro-hotplates were fabricated on commercial GaN-capped AlGaIn/GaN-on-Si wafers grown by metal-organic chemical vapor deposition (MOCVD). The wafer had a sheet resistance of  $\sim 409 \Omega/\square$  at room temperature. The electron mobility was measured to be  $\sim 1400 \text{ cm}^2/\text{V}\cdot\text{s}$  and the sheet electron density  $\sim 0.9 \times 10^{13} \text{ cm}^{-2}$ . The fabrication process (Fig. 4) starts with a mesa etch using a chlorine/boron chloride ( $\text{Cl}_2/\text{BCl}_3$ ) plasma to define the 2DEG heater geometry. Then, Ti/Al/Pt/Au metal contacts were e-beam evaporated and patterned with lift-off. A rapid thermal anneal at 850°C for 35 seconds in a  $\text{N}_2$  ambient was conducted to

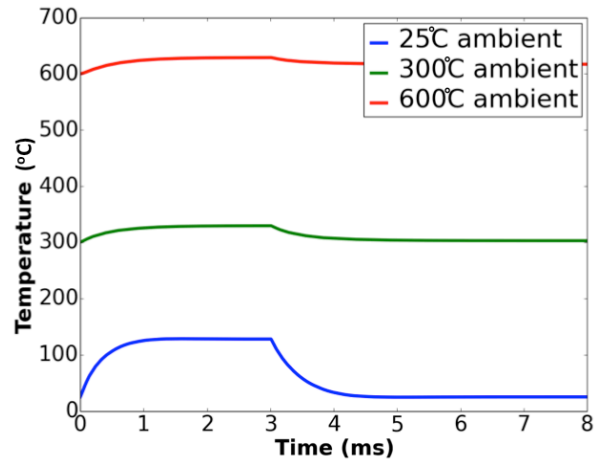


Figure 3: Simulated transient responses of spiral four-arm AlGaIn/GaN micro-hotplate. In the simulation, a heating voltage (15V) was applied at  $t = 0$ , and removed at  $t = 3$  ms.

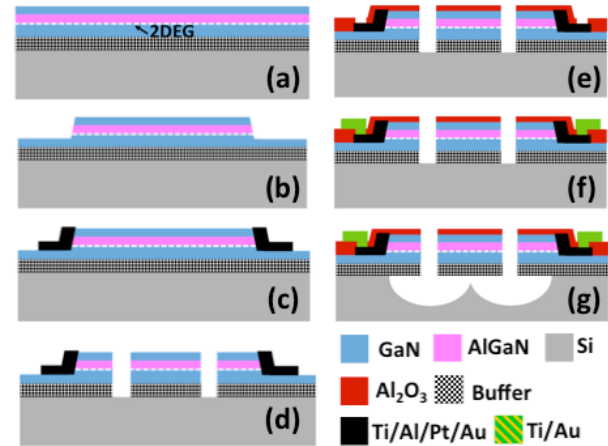


Figure 4: Process used to micro-fabricate the fully-suspended AlGaIn/GaN micro-hotplate with 2DEG heater.

make the contacts Ohmic and improve reliability at high temperatures [22]. Silicon dioxide ( $\text{SiO}_2$ ) was then deposited by plasma-enhanced chemical vapor deposition (PECVD). The GaN and buffer layers were patterned with  $\text{Cl}_2/\text{BCl}_3$  plasma using the PECVD  $\text{SiO}_2$  hard mask to define the micro-hotplate membrane shapes. The  $\text{SiO}_2$  was stripped with buffered oxide etch (BOE) after the plasma etch. Then, alumina ( $\text{Al}_2\text{O}_3$ ) was deposited with plasma-enhanced atomic layer deposition (PE-ALD) for passivation of the micro-hotplate surface.  $\text{Al}_2\text{O}_3$  was later patterned with BOE to expose metal contacts for interconnection, and to expose the gaps between the 2DEG heater arms and the central plate for later  $\text{XeF}_2$  release of the membrane. The micro-hotplate membrane was released from Si substrate with  $\text{XeF}_2$  vapor. The optical image of a fabricated AlGaIn/GaN micro-hotplate is shown in Fig. 2a with a surface temperature map during operation ( $\sim 90$  mW power input) imaged by an infrared camera (Fig. 2b).

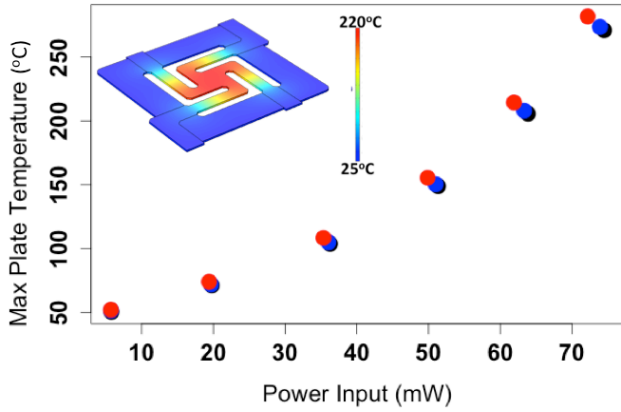


Figure 5: Interpolated heating characteristics of three microfabricated AlGaIn/GaN micro-hotplates at ambient temperature of 25°C. The inset shows the simulated temperature profile of the micro-hotplate.

## CHARACTERIZATION

The AlGaIn/GaN micro-hotplates were electrically characterized at various ambient temperatures (from 25°C to 600°C) in air using a high temperature probe station (Signatone Inc.) and a semiconductor parameter analyzer (Agilent B1500A). Interpolation of electrical measurements and FEA simulation results were used to approximate the maximum plate temperatures. The characterization procedure is as follows:

- The electrical resistance values of several micro-hotplates were measured at various ambient temperatures up to 600°C in air.
- A numerical fit of the measured resistances versus ambient temperature was obtained using a least-squares quadratic model.
- The temperature-dependent electrical resistivity was calculated from the fitted quadratic model and fed into the FEA model (the model is shown in the inset of Fig. 5).
- The FEA model was used to compute the maximum plate temperatures ( $T_{\max}$ ) achieved by applying various voltages at various ambient temperatures, as well as the total current flowing through the micro-hotplate. The resistance ( $R$ ) of the micro-hotplate was then calculated by dividing the applied voltages with the corresponding currents.
- The  $R$  versus  $T_{\max}$  ( $R$ - $T_{\max}$ ) curves at various ambient temperatures were obtained, and fitted with least-square linear regression models.
- The resistance values of the micro-hotplates under various applied voltages at various ambient temperatures were measured using the high-temperature probe station and SPA.
- The maximum plate temperatures of the micro-hotplates at different ambient temperatures were interpolated using the fitted  $R$ - $T_{\max}$  curves and the measured resistances.

The characterization results using the interpolation method are shown in Figs. 5 and 6. As shown in Fig. 5, an input power of ~75 mW generates a maximum plate temperature of about 270°C in 25°C ambient temperatures. This corresponds to a heating efficiency of about 3°C/mW, which can be further increased by geometry optimization (Fig. 1). The fabricated micro-hotplates demonstrated successful heating operation at elevated ambient temperatures (300°C to 600°C) in air using a high-temperature probe station (Fig. 6). As the ambient temperature is increased, the maximum temperature rise on the plate with respect to the ambient

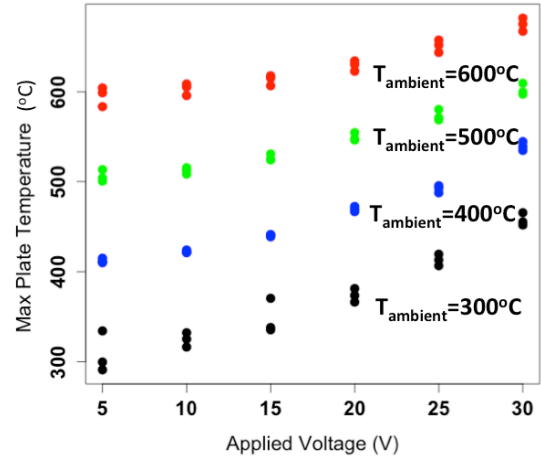


Figure 6: Operation of multiple AlGaIn/GaN micro-hotplates at elevated ambient temperatures up to 600°C in air.

Table 2: Summary of uncertainty analysis of the maximum temperature values obtained from the characterization procedure.

Error source	Estimated Error
The error induced by the simplifying assumptions made in FEM	Average ~ 3.4% (Max ~9%)
FEM convergence	<0.1%
Error in quadratic fit of measured resistances	Average ~2.6% (Max ~9%)
Uncertainty induced by the variation in released membrane width (10 $\mu\text{m}$ variation)	~0.13%
Error induced by the uncertainty in thermal conductivity and geometric parameters	Approx. zero (Fig. 9)
Neglecting contact resistance	<0.25%
SPA measurement error	Approx. zero
Chuck temperature reading error	<4% (1°C error at 25°C)
Error in linear fit of $R$ - $T_{\max}$ calibration curves	Average ~0.15% (Max ~ 0.2%)
Total	Average ~11% (Max ~22%)

temperature is decreased because the mobility of electrons in 2DEG is decreased due to increased phonon scattering [23]. Thus, the electrical conductivity of 2DEG is decreased and less current can be pumped through into the micro-hotplates for self-heating at higher temperatures. Nevertheless,  $T_{\max}$  of ~680°C was achieved in 600°C ambient with an applied voltage of 30 V (Fig. 6).

## UNCERTAINTY ANALYSIS

The uncertainty sources for the maximum plate temperatures obtained from the characterization procedure are summarized in Table 2. The total average uncertainty was estimated to be approximately 11%. The three most significant sources of uncertainty are 1) neglecting heat loss to air and radiation in FEA, 2) least-square quadratic fitting of measured resistance values with respect to ambient temperatures, and 3) the error in chuck temperature readings. It should be noted that the uncertainties in the thermal conductivity, thickness and 2D layout geometry of the micro-hotplate do not induce errors in the FEA-computed  $R$ - $T_{\max}$  curves. This is validated by the FEA: the ( $R$ ,  $T_{\max}$ ) pairs resulting

from different thermal conductivities, thicknesses, and L/W values all fall on one single curve, which is the one generated by varying the voltages applied to a nominal device geometries with material properties summarized in Table 2.

## DISCUSSION AND CONCLUSION

2DEG-heated AlGaIn/GaN micro-hotplates have been modeled, microfabricated, and characterized in this work. A heating efficiency of approximately 3°C/mW has been achieved by the device prototypes, which is a suitable activation power for many sensing applications. To further improve the heating efficiency, longer and thinner heater arms can be utilized. In addition, to preserve mechanical robustness while enhancing heating efficiency, spring-shapes (or “zigzag” shapes) heater arm layout can be employed. A reduction in heating voltage for a certain maximum plate temperature can be achieved by reducing the sheet resistance of the AlGaIn/GaN heterostructure through material optimization. Sheet resistances values of near 300 Ω/□ and lower have been reported in literature [24]. In conclusion, 2DEG-heated micro-hotplates have been successfully fabricated and operated in air and demonstrated heating temperatures as high as 680°C (from 600°C ambient temperature), supporting the development of monolithic AlGaIn/GaN microsystems for in-situ chemical sensing in high-temperature environments.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Dr. Philippe Jansen and Texas Instruments Inc. (TI).

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