Supporting Information for

Thermo-dynamic Studies of β-Ga_2O_3 Nano-membrane Field-effect Transistors on Sapphire Substrate

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1. TR measurement set-up and timing principles

During the TR imagining measurement as shown in Fig. S1(a), the device is biased with a V_{DS} pulse to generate heat during the measurement, the device is also illuminated by a high-speed LED pulse, and a synchronized charge coupled device (CCD) camera is used to capture the reflected image. Fig. S1(b) is the timing mechanism of the TR imagining. Device is periodically turned ON and OFF by the V_{DS} pulse to heat up and cool down the channel. Through controlling the LED delay τ with respect to the starting point of V_{DS} pulse t_0, the TR imaging can capture the transient heating and cooling kinetics with 50-ns resolutions. The τ will serve as the camera shutter to control the LED illumination. Each V_{DS} cycle will make an image to capture the thermal status of the device at a given τ. Finally, an average of those images increase signal-to-noise ratio and produces a high-resolution ΔT (x, y, t).

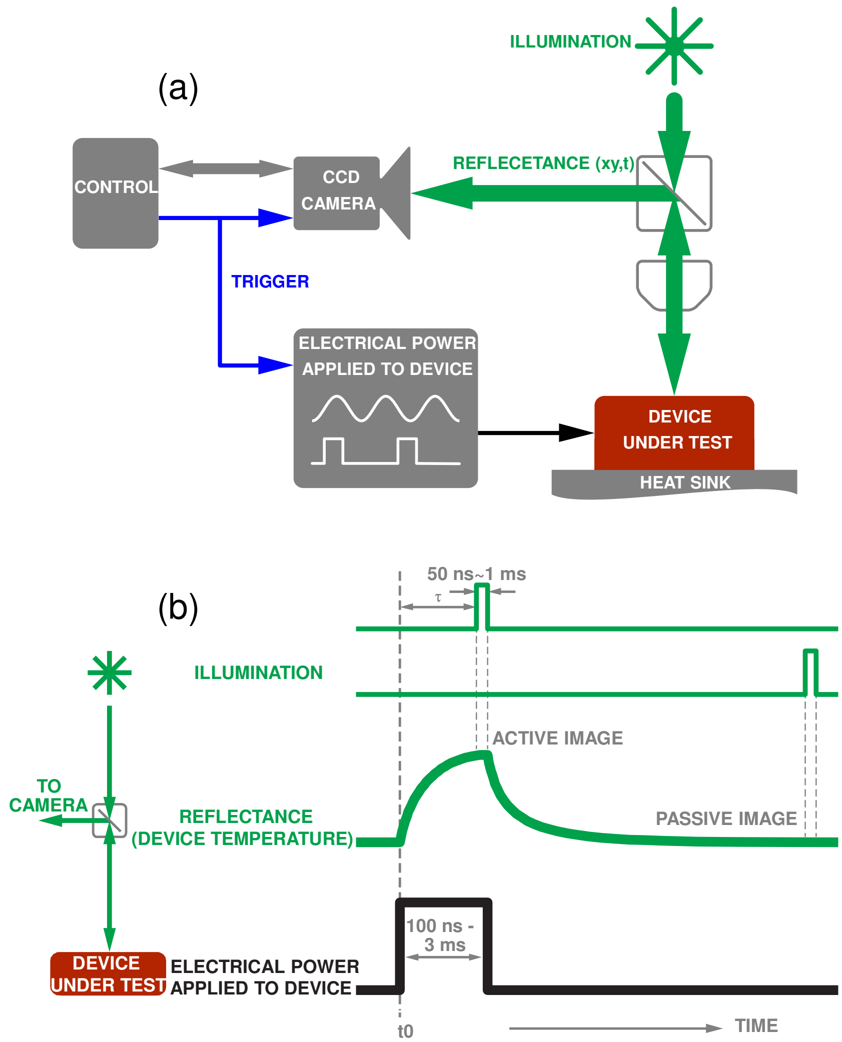

Figure S1. (a) TR measurement set-up configurations. Pulse generator (V_{DS}) is applied to generate heat on the device under test. A control computer triggers the LED to illuminate the device and the CCD camera to capture the reflectance change at a given delay with respect to V_{DS}. (b) Timing diagram for TR measurement at a given LED time delay τ.

2. TR coefficient calibration and photography of TR measurement equipment

During calibration of thermo-reflectance coefficient, the sample is thermally cycled by external micro-thermoelectric stage. Then the sample surface temperature is monitored by a micro-thermocouple and the CCD camera is used to capture the reflectance change to get the reflectance coefficient by comparing the reflectance change and micro-thermocouple temperature, as shown in Fig. S2(a). Fig. S2(b) is the photography of the TR measurement instrument and sample stage used for this experiment.

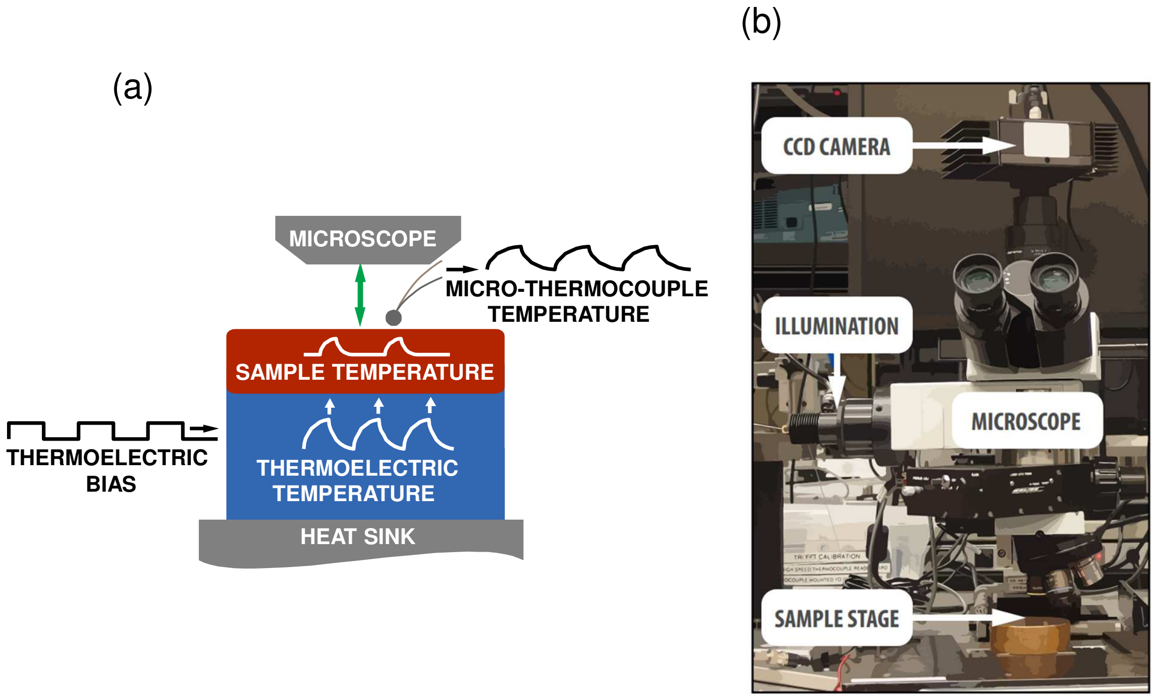

Figure S2. (a) TR coefficient calibration set up and working principles. (b) Photograph of the TR measurement instrument and sample stage used for measuring the TR of GOOI FET.

3. Simulation Mesh build up

The finite-element method (FEM) simulation is started with mesh build up. The triangular mesh is constructed as Fig. S3. The constructed GOOI FET structure has a similar structure as our fabricated device. The simulated substrate has a length, width, and height of 15 μm, 15 μm, 10 μm, respectively.

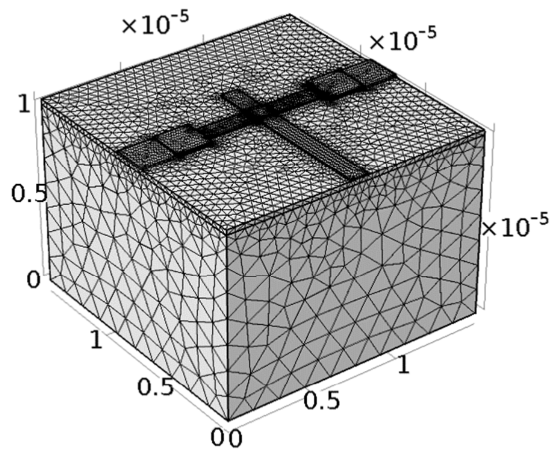

Figure S3. Mesh build up for GOOI FET.

4. Heat pulse generation function for transient measurement

During the transient TR imagining and thermal simulation, the device is biased by a V_{DS} pulse to generate the device power pulse, as shown in Fig. S4. This pulse has 1 μs of heating followed by 1 μs of cooling with the pulse duty cycle of 10%. The applied power is 0.07 kW/mm^2 and 0.22 kW/mm^2 for GOOI FET on SiO_2/Si and sapphire, respectively, to achieve a similar device temperature.

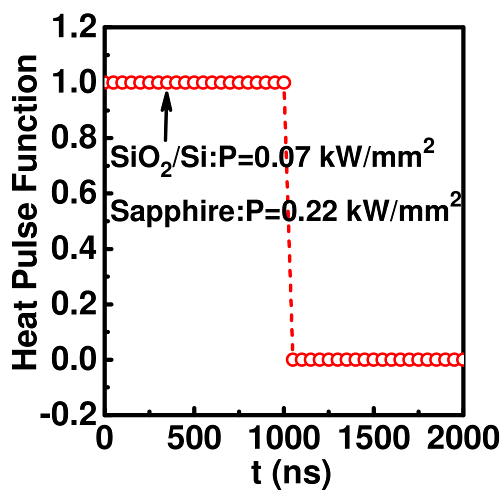

Figure S4. Heat pulse generation function for transient measurement.

5. A simplified 1D equivalent thermal circuit model of GOOI FET on sapphire

To analysis and estimate the thermal response for the dynamic measurement, a simplified 1D equivalent thermal circuit model is adopted by involving a thermal resistor and a capacitor, as shown in Fig. S5. The 1D model is valid due to majority of the heat at the gate region is directly dissipated through sapphire substrate.

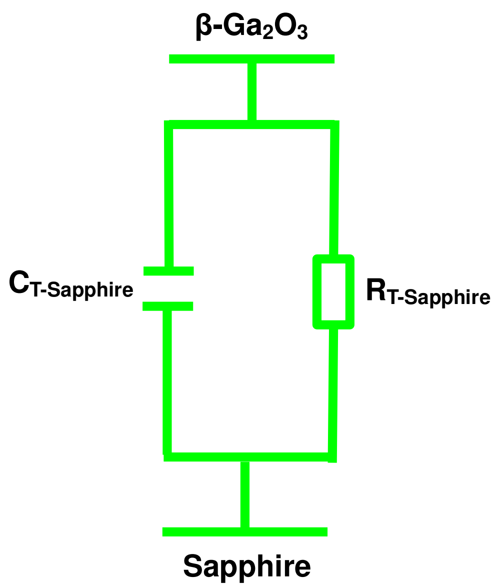

Figure S5. Simplified 1D equivalent thermal circuit model of GOOI FET on sapphire substrate.

6. List of major material parameters used for thermal resistance calculation and finite-element method simulation

Table S1: List of major material parameters used for thermal resistance calculation and finite-element method simulation.

Material	Thermal conductivity (W/m·K)	Mass density (Kg/m^3)	Specific Heat (J/Kg·K)
β-Ga_2O_3	10	6000	800
SiO_2	1.5	2200	700
p++ Si	80	2330	761
Sapphire	40	3900	753