Tactile Sensing at Cryogenic Temperatures Using MichTac Sensors Based on GaN Nanopillar LEDs

Nathan Dvořák[1] **and Pei-Cheng Ku**[1*]
[1]*Department of Electrical Engineering and Computer Science, University of Michigan, 1301 Beal Ave, Ann Arbor, Michigan 48109-2122, USA*
**peicheng@umich.edu*

Abstract: Experiments successfully established the feasibility of a nanopillar-LED-based tactile sensor showing tactile perception at extremely cold temperatures.

1. Introduction

Tactile sensing plays an important role in robotic systems for space exploration. The hull of the International Space Station can reach a temperature ranging from -157ºC in darkness to 120ºC in sunlight. Tactile sensors suitable for extravehicular applications must function across a wide temperature range and withstand radiation and electromagnetic interference (EMI). Most tactile sensors designed for robotics with advanced performance either fail to operate at an extremely low temperature or require electronics near the force transducer, which makes them subject to EMI. Recently, we developed the MichTac tactile sensor based on an array of GaN nanopillar LEDs as force transducers [1]. The image of the LEDs directly corresponds to a map of the external shear force incorporating both the magnitude and direction information, which have been shown to enable surface texture and microstructure detection. In this work, we present the full functionality of the MichTac sensor at a liquid nitrogen temperature (-157ºC) and preliminary data suggesting a successful operation up to 400ºC. With remote optical excitation and image detection via a multimode optical fiber [2], the MichTac sensor can potentially bring advanced tactile sensing performance to space applications.

2. Methods

The MichTac sensor was fabricated from a commercial green-emitting GaN LED epi wafer. Each nanopillar LED has an elliptically shaped cross-section with dimensions of 120 nm x 360 nm and a height of 650 nm. While the nanopillar LEDs can be electrically biased [3], this work used an external 405 nm diode laser to remotely excite them. The detailed fabrication processes can be found in Ref. [1]. The LED image was detected using an off-the-shelf CMOS image sensor. A pair of nanopillar LEDs with orthogonally oriented ellipses were used to detect the force's direction. The LED's intensity is more sensitive to a force parallel to the ellipse's long axis.

The operation principle of the MichTac sensor can be found in Ref. [1]. In summary, the external shear force creates a strain field in the LED's quantum well region, laterally shifting the electrons and holes and reducing the emission intensity. The intensity change ΔI can be shown to be linearly proportional to the magnitude of the shear force, at least in the range of interest for tactile sensing. The proportionality constant depends on the dimension of the nanopillar. Hence, one can create an asymmetry in force sensitivity in two directions to help detect the force's direction in addition to the magnitude.

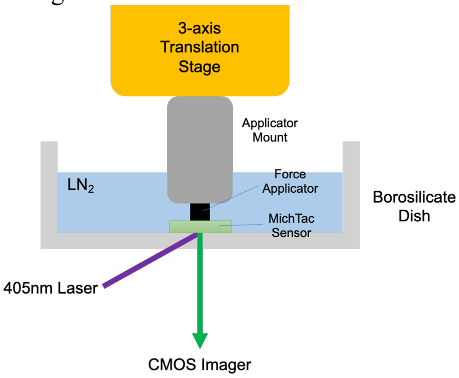

Figure 1 Experimental setup to test the MichTac sensor's functionality at the liquid nitrogen temperature. Only the sensor and the force applicator are kept at a low temperature. Sensor excitation and image detection are both performed remotely at room temperature.

We simulated a cryogenic environment with a proof of concept, bench-top experiment by submerging the MichTac sensor and a force applicator in liquid nitrogen, as illustrated in Figure 1. A 5 x 5mm^2 polystyrene foam square was used as a force applicator. Manipulation of the force applicator was achieved via a 3-axis translation stage. The tactile sensor was mounted to the bottom of a shallow borosilicate dish via copper tape with the substrate facing down. We ensured the dish held enough liquid nitrogen for temperature stabilization and optical transparency around the sensor, away from the boiling liquid surface.

Force measurements were achieved by first bringing the force applicator to about 1mm surface of the sensor within the borosilicate dish. Next, the dish was filled with liquid nitrogen. We waited until the liquid nitrogen stopped boiling to indicate the temperature had stabilized. The force applicator was then brought into contact with the tactile sensor. We will refer to this initial contact state as the unsheared state. We recorded the nanopillar emissions with the CMOS imager. We moved the force applicator across the tactile sensor using the translation stage. For every 50µm of translation, the nanopillar's emissions were recorded until 200µm of translation were reached; these recordings will be referred to as the sheared state. We completed two translations during this experiment, one parallel and one perpendicular to the long axis of the nanopillar's elliptical cross-section.

3. Results

Each sheared nanopillar emission is normalized against the unsheared emission, thus yielding the relative intensity of the LED emission. The results are shown in Figure 2. Black squares and dashed line refer to a translation parallel to the long axis of the nanopillars' elliptical cross-sections, and red circles and dashed line refer to a translation perpendicular to the long axis of the nanopillars' elliptical cross-sections. The results agreed with the previous report [1] and showed the sensitivity to both the force's magnitude and direction.

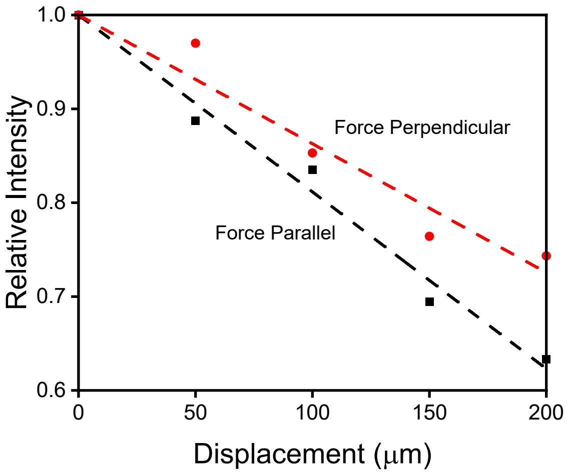

Figure 2. Relative emission intensity versus shear pressure applied by a 5 x 5mm^2 polystyrene square at the liquid nitrogen temperature (−196 °C). Black (red) squares (circles) represent the sensors' relative intensities when the force applicator is translated parallel (perpendicular) to the long axis of the nanopillars' elliptical cross-section. The dashed lines represent linear fits of the data points of the same color.

4. Conclusion

We have demonstrated the functionality of the MichTac sensor at a cryogenic temperature. The MichTac sensor was designed with a spatial resolution, response time, and sensitivity suitable for a robotic gripper specializing in poise estimation. Moreover, only the sensor's passive transducer must be exposed to extreme environments. The current data supports a future version in which all electronics can be shielded from radiation and EMI and be connected to the transducer via an optical fiber.

5. References

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