# A FAST UNCOOLED INFRARED NANOBOLOMETER FEATURING A HYBRID-PLASMONIC CAVITY FOR ENHANCED OPTICAL RESPONSIVITY

*Floria Ottonello Briano, Marco Colangelo, Carlos Errando-Herranz, Hans Sohlström, and Kristinn B. Gylfason*

Micro and Nanosystems, KTH Royal Institute of Technology, Stockholm, Sweden

## ABSTRACT

We demonstrate the first uncooled single-nanowire-based infrared bolometer to detect sub-mW optical signals up to MHz frequencies. The bolometer consists of a Pt nanowire on a suspended silicon hybrid-plasmonic cavity, and exhibits enhanced optical responsivity compared to nanowires on unstructured and non-suspended substrates. Low-cost monolithically integrated infrared detectors are needed for the rapidly growing field of silicon photonic sensors. The high speed of our nanobolometer enables advanced modulation schemes for noise reduction and avoidance of low-frequency thermal cross-talk, as well as power saving by pulsed operation. Furthermore, its simple integration and small footprint make it a cost effective detector for sensing applications.

## INTRODUCTION

Optical sensors based on integrated silicon photonic waveguides are well suited for mass-production, and have important applications in distributed gas and chemical sensing [1, 2, 3]. However, the integration of light sources and detectors remains a challenge [4, 5, 6]. To preserve the benefits of silicon photonics, detectors need to be small, have low-power consumption, and be easily integrable onto waveguides using standard MEMS fabrication. Single-nanowire bolometers fulfil these requirements. Moreover, their small size makes them capable of high speed operation, enabling low power operation and advanced modulation schemes. Platinum nanowires offer chemical inertness up to high temperatures, a linear relation between resistance and temperature over a wide range, and ease of integration in systems on chip. In previous work, single-Pt-nanowire bolometers have been characterized under DC conditions [7], and Au [8] and ZnO [9] nanowires have shown detection up to kHz frequencies. However, MHz-rate optical detection by nanowire bolometers has not been shown.

Here we present a new uncooled single-Pt-nanowire bolometer featuring a hybrid-plasmonic cavity that enhances the detector's responsivity. Characterizing the bolometer's response, we experimentally demonstrate infrared light detection up to MHz frequencies.

## DESIGN AND CHARACTERIZATION

Our hybrid-plasmonic cavity (HPC) bolometer consists of a Pt nanowire on a suspended Si beam, as presented in Fig. 1. The nanowire is 500 nm wide, 60 nm thick, and 3.5 µm long. The Si beam, as long as the nanowire, is 1 µm wide and 220 nm thick. The nanowire was fabricated by electron-beam lithography, Pt evaporation, and lift-off. A 7 nm thick layer of chromium was deposited prior to the Pt to improve adhesion. The Si beam was patterned into the substrate, a SOI substrate with 220 nm thick Si device layer and 2000 nm thick buried thermal oxide (BOX) layer, by electron-beam lithography and plasma dry etching, followed by hydrofluoric acid (HF) vapor etching.

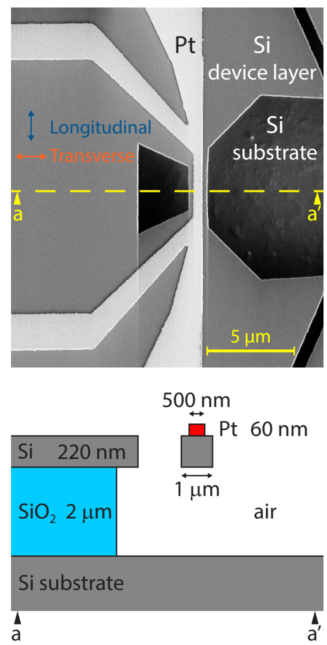


*Figure 1: The HPC bolometer: SEM image (top) and cross-section (bottom). It consists of a 500 × 3500 × 60 nm Pt nanowire on a 1000 × 3500 × 220 nm suspended Si beam that acts as a hybrid-plasmonic cavity.*

We measured the response of the HPC bolometer to longitudinally and transversely linearly polarized laser light of wavelength 1.55 µm, modulated at frequencies from 75 Hz to 1.13 MHz, using the setup schematized in Fig. 2. The longitudinal polarization was oriented parallel to the length of the Pt nanowire and the transverse polarization was oriented perpendicularly to it. The Pt nanowire bolometer was connected in a four-wire configuration: a 1 mA DC bias was applied to the two outer contacts, and the voltage response was measured across the two inner contacts. The bolometer was illuminated through a single-mode optical fiber with a gaussian mode profile of mode field diameter 10 µm. The optical power delivered by the fiber was 0.45 mW.

To further investigate the nature of the bolometer's re-

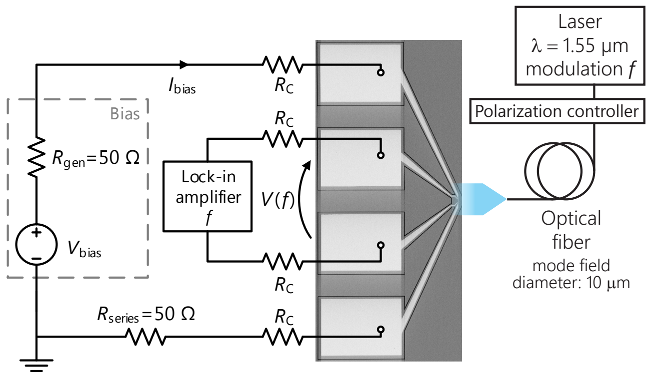


*Figure 2: Schematic of the setup used to characterize the HPC bolometer and the cavity-less bolometers. A laser provides the modulated, linearly polarized light of wavelength 1.55 µm used to measure the bolometers' response. The light, whose polarization orientation is varied with a polarization controller, is brought onto the bolometers by an optical fiber with mode field diameter of 10 µm. The Pt nanowire of the bolometers is biased with a DC current of 1 mA and the voltage response is measured with a lock-in amplifier.*

sponse, we operated the bolometer while raster scanning the optical fiber over an area of $54 \times 76\ \mu\text{m}^2$, and so obtained a 2D scan of the bolometer and its surroundings. We performed this measurement at the fixed frequencies of 11 kHz and 1.05 MHz.

All measurements were performed at room temperature.

We compare the response of the HPC bolometer to that of two reference non-suspended, cavity-less Pt nanowire bolometers, shown in Fig. 3. They have the Pt nanowire,

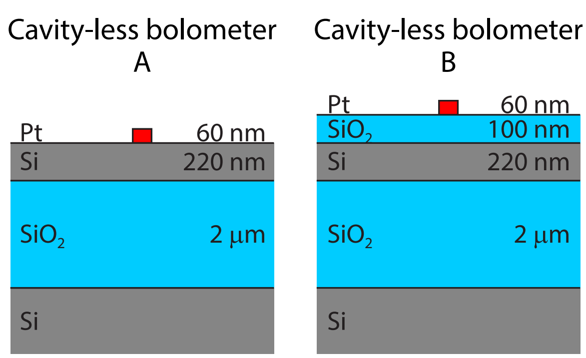


*Figure 3: Cross-sections of the cavity-less bolometers A (left) and B (right).*

equivalent to the one previously described, on an unstructured substrate. This is, for the cavity-less bolometer A, the specified SOI substrate, with 220 nm thick Si layer and a 2000 nm thick $SiO_2$ layer, and for the cavity-less bolometer B the SOI substrate with an additional top 100 nm thick $SiO_2$ layer. This $SiO_2$ layer was deposited by plasma-enhanced chemical vapor deposition (PECVD).

## RESULTS AND DISCUSSION

The voltage response of the HPC bolometer and of the two cavity-less bolometers as a function of the incident light modulation frequency is displayed in Fig. 4. The HPC

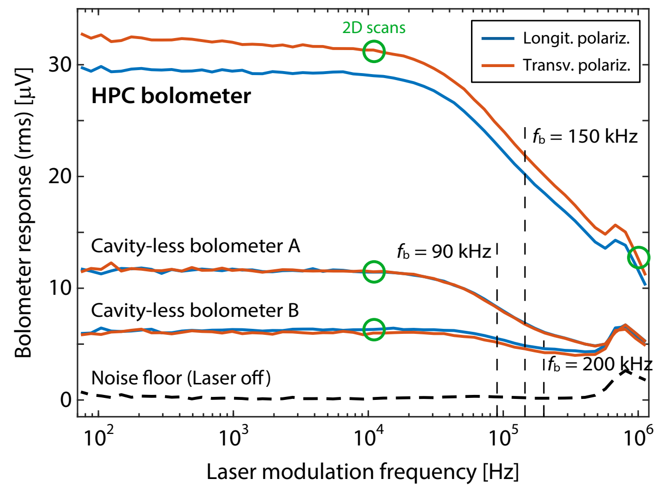


*Figure 4: The voltage response of the HPC bolometer and of the cavity-less bolometers A and B as a function of the modulation frequency of the longitudinally and transversely polarized incident light. Despite having bulk thermal cut-off frequency of 150 kHz, the HPC bolometer provides a relevant response of optical nature up to above 1 MHz.*

bolometer provides, in the low-frequency operation regime, a response almost three times larger than bolometer A and five times larger than bolometer B. Moreover, it exhibits a stronger response to transversely polarized light than to longitudinally polarized light. The stronger response of the HPC bolometer, compared to the cavity-less bolometers, is partially justified by the better thermal insulation of its absorptive element from the substrate, due to the removal of the BOX $SiO_2$ layer. A better insulation corresponds to a smaller thermal conductance to the substrate, and hence a larger temperature increase in the Pt nanowire. However, this does not explain the difference in the response to different polarizations.

We found that two phenomena contribute to the HPC bolometer's response: a bulk heating contribution and a local optical contribution. The bulk heating contribution is caused by the heating of the substrate material surrounding the nanowire, due to the large size of the incident light spot. The light spot delivered by the optical fiber has a diameter of about 10 µm, much larger than the size of the Pt nanowire, and thus illuminates both the nanowire and its surroundings. When the material heats up due to the incident light, part of the generated heat is conducted to the the Pt nanowire, contributing to the increase of its temperature, hence electrical resistance, according to the linear relation $R = R_0 + R_0\alpha(T - T_0)$, and consequently voltage response. The magnitude and speed of this heating contribution depend on the volume and thermal properties of the materials involved, as explained by the characterization and modeling of the thermal impedance of the

HPC and cavity-less bolometers structures [10].

In addition to the bulk heating, a local optical effect contributes to the HPC bolometer's repsonse. The Si beam under the Pt nanowire supports hybrid-plasmonic modes, as confirmed by FEM modal analysis. If the light incident on the bolometer matches these modes, it couples with them and it optically resonates in the beam. Hence the beam acts as a resonant cavity that improves the light absorption, leading to an enhancement in the bolometer's response. This effect is polarization-dependent according to the polarization of the hybrid-plasmonic cavity modes. The modal analysis shows that the modes, one of which is depicted in Fig. 5, are mainly transversely polarized. This explains the stronger response of the HPC bolometer to transversely polarized light, compared to longitudinally polarized light.

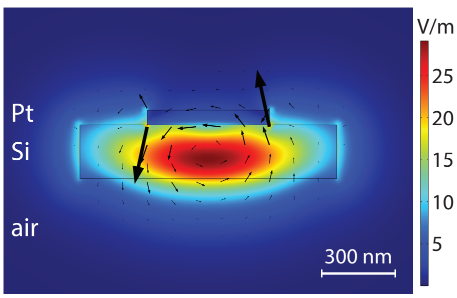


*Figure 5: One of the hybrid-plasmonic modes supported by the HPC bolometer structure, simulated by FEM modal analysis. The color map represents the electric field norm and the arrows the field magnitude and orientation.*

The most relevant aspect of this local optical effect is its speed, compared to the thermal effect. The bulk heating contribution attenuates above 20 kHz and drops by 3 dB at the bulk thermal cut-off frequency $f_b = 150$ kHz. The optical contribution, instead, allows the HPC bolometer to provide a response up to above 1 MHz. In comparison, the cavity-less bolometers A and B do not show a relevant response above their bulk cut-off frequencies, 90 kHz and 200 kHz respectively.

We further verified the optical nature of the high-frequency response comparing a 2D raster scans of the HPC bolometer performed with incident light modulated at 11 kHz, i.e. below the bulk thermal cut-off frequency, and a 2D scan performed with incident light modulated at 1.05 MHz, i.e. above the bulk thermal cut-off frequency. The scans are displayed in Fig. 6. The 11 kHz 2D scan reveals an active area significantly larger than just the Pt nanowire, indicating that the material in its surroundings contributes to the bolometer's response with a bulk thermal effect. The 1.05 MHz 2D scan shows instead a much smaller active area, which can be identified as the nanowire-cavity structure, despite the limited resolution of the scan due to the size of the incident light spot. This scan, indicating that the surroundings of the nanowire do not participate in the light detection, excludes a thermal contribution to the bolometer's response at high frequencies, and confirms instead its optical nature.

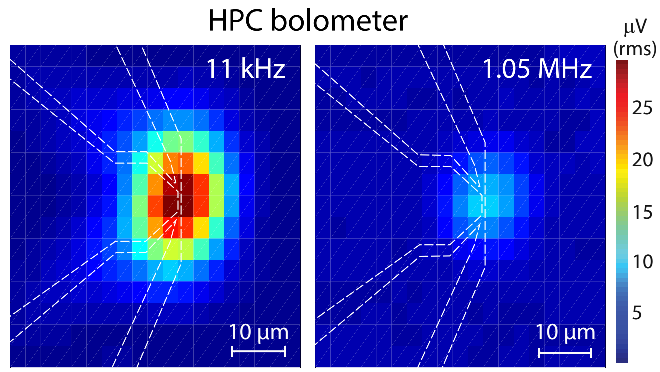


*Figure 6: The response of the HPC bolometer to the scanning light spot has predominantly thermal nature for incident light modulated at 11 kHz (left) and optical nature at 1.05 MHz (right). The incident light was transversely polarized.*

The 2D scans of the cavity-less bolometers, displayed in Fig. 7, performed with incident light modulated at 11 kHz, confirm the smaller magnitude of their responses, particularly that of bolometer B, and their thermal nature. We performed 2D scan with incident light modulated at 1.05 MHz on these bolometers as well, but measured no relevant response. This verifies the absence of the optical contributions in these devices, as opposed to the HPC bolometer.

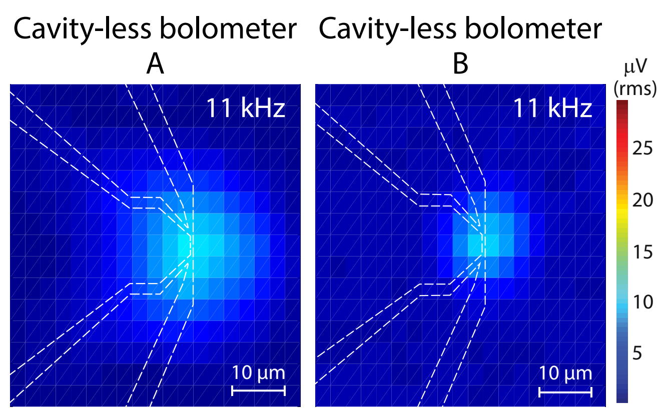


*Figure 7: The response of the cavity-less bolometers A (left) and B (right) to the scanning light spot has thermal nature. The incident light was modulated at 11 kHz and longitudinally polarized.*

We assessed the responsivity $R = V/P$ of the HPC bolometer relating its voltage response $V$ to the total optical power $P$ delivered by the optical fiber. The $P$ value that we applied in the calculation is slightly higher than the power actually delivered to the bolometer, because it was measured under optimal conditions, connecting the optical fiber cable directly to a detector. Moreover, we did not normalize the power $P$ by the bolometer's area because, as described above, the active area varies with the light modulation frequency due to the bulk thermal effect, and considering only the Pt nanowire area, as often done in literature, would artificially inflate the responsivity value. The responsivity of our HPC bolometer is 70 mV/W in the low-frequency operation regime, and stays above 25 mV/W up to 1.13 MHz. We compared the performance of our bolometer, evaluated as responsivity-bandwidth product $R \cdot f$, to that of other two uncooled, optically characterized, single-nanowire IR bolometers from the literature [8] [9]. As illustrated in Fig. 8, even though our HPC bolometer has lower responsivity than the other devices, it achieves the highest $R \cdot f$ product and thus best performance.

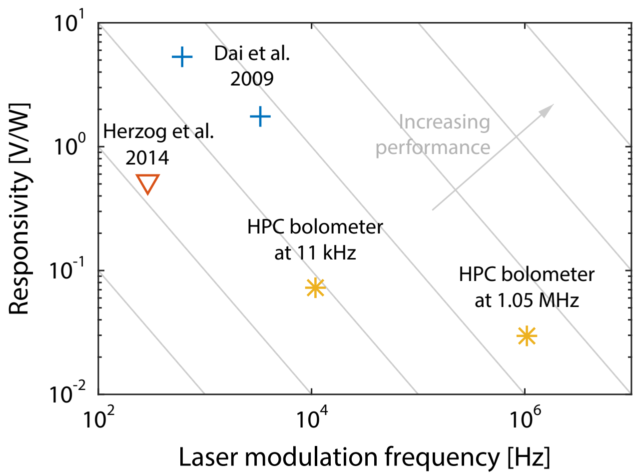


*Figure 8: The HPC bolometer, compared to other uncooled, optically characterized, single-nanowire IR bolometers from the literature, exhibits the best performance in terms of responsivity and speed.*

## CONCLUSIONS

We presented an uncooled infrared bolometer featuring a Pt nanowire on a suspended Si hybrid-plasmonic cavity, and showed that it exhibits enhanced response and large bandwidth, compared to similar non-suspended cavity-less bolometers. We showed that the response enhancement is due not only to an increased thermal contribution caused by the thermal insulation of the nanowire, but also to an optical resonance effect produced by the Si cavity, which supports hybrid-plasmonic modes.

We demonstrated that the bolometer has a responsivity of 70 mV/W in its low-frequency operation regime and, despite having a bulk thermal cut-off frequency at 150 kHz, it maintains a responsivity above 25 mV/W up to 1.13 MHz. This makes it the first uncooled single-nanowire-based infrared bolometer to detect sub-mW optical signals up to MHz frequencies.

The high speed of our nanobolometer enables advanced modulation schemes for noise reduction and avoidance of low-frequency thermal cross-talk, as well as power saving by pulsed operation. High speed and low power consumption, together with simple integration, low-cost, and small footprint, make our bolometer uniquely suited for integration into silicon photonic systems for sensing applications.

## ACKNOWLEDGMENTS

This work was partially funded by Sweden's Innovation Agency (VINNOVA grants 2016-01655 and 2016-02328) and Stockholm County Council (SLL grant 20150910).

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## CONTACT

Floria Ottonello Briano, floria@kth.se