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***In Situ* Observation of Carbon Nanotube Layer Growth on Microbolometers with Substrates at Ambient Temperature**

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Abstract

Carbon nanotubes (CNTs) have near unity infrared (IR) absorption efficiency, making them extremely attractive in IR imaging devices. Since CNT growth occurs at elevated temperatures, integration of CNTs with IR imaging devices is challenging and has not yet been achieved. Here we show a strategy for implementing CNTs as IR absorbers using differential heating of thermally-isolated microbolometer membranes in a C₂H₂ environment. During the process, CNTs were catalytically grown on the surface of a locally-heated membrane while the substrate was maintained at an ambient temperature. CNT growth was monitored *in situ* in real time using optical microscopy. During growth, we measured the intensity of light emission and the reflected light from the heated microbolometer. Our measurements of bolometer performance show that the CNT layer on the surface of the microbolometer membrane increases the IR response by a factor of (2.3 ± 0.1) (mean $\pm$ one standard deviation of the least-squares fit parameters). This work opens the door to integrating near unity IR absorption, CNT-based, IR absorbers with hybrid complementary metal-oxide-semiconductor focal plane array architectures.

Introduction

Infrared (IR) imaging in the wavelength range from 8 μm to 14 μm , also known as thermal imaging, has found widespread applications spanning disparate fields of engineering, life and physical sciences. Room-temperature and cooled thermal imagers have been used in preventive maintenance, night vision, medical imaging, security and space applications¹. Heat sensing, uncooled microbolometers² in the form of focal plane arrays (FPAs) represents a class of integrated, two-dimensional ensemble thermal detector arrays with multiplexed readout. In contrast to cryogenically-cooled devices, uncooled IR microbolometers have numerous advantages including higher reliability, reduced power consumption and smaller physical dimensions. Modern microbolometer devices, operating

Supplementary materials

See supplementary materials for microbolometer resistance and temperature coefficient of resistance measurement, evaluation of microbolometer thermal parameters, microbolometer response to varying V_b , details of emission measurement during CNT growth, resistance measurement during CNT growth, emission measurement from the microbolometer with CNTs, reflection measurement from bolometer membrane during CNT growth and calculation of blackbody radiant exitance.

at room temperature, are based on thermally isolated membrane architectures with integrated temperature sensors. The incident radiation, absorbed as heat, increases the temperature of the microbolometer membrane. The temperature change (ΔT_{IR}), proportional to the power of incident radiation (P_{IR}), is given by:

$$\Delta T_{\text{IR}} = \frac{P_{\text{IR}}}{G}, \quad (1)$$

where G is thermal conductance of the microbolometer.

The FPA imagers are mass produced using Si-based complementary metal-oxide-semiconductor (CMOS) architectures. The imager consists of an array of pixels, with each pixel connected to a read-out integrated circuit. The microbolometer pixels are created using microelectromechanical systems (MEMS) technology. The microbolometer membranes are typically made from various CMOS-compatible materials such as silicon dioxide (SiO_2), silicon nitride, amorphous Si and SiGe. Mid IR absorption (η), in range of interest from 8 μm to 14 μm of these materials, depends on the film thickness and composition. For instance, η for SiO_2 with thickness of $\approx 0.6 \mu\text{m}$ ranges from $\approx 35\%$ to $\approx 48\%$ ⁴. The key challenge is then to maximize η while using a CMOS compatible process. Several developed strategies to increase η suffer from a significant increase in processing costs and complexity.

The first reported IR absorbing carbon nanotube (CNT) layer was implemented on the surface of a pyroelectric detector⁵ sparking an interest in CNTs as an electromagnetic radiation absorber^{6,7}. Controlled placement of vertically-aligned CNT layers require growth in a chemical vapor deposition (CVD) reactor at elevated temperatures above 550 $^\circ\text{C}$ ⁸, using lithographically patterned catalytic materials⁹. The highest temperature that CMOS devices can withstand is typically below 475 $^\circ\text{C}$. This value represents the eutectic temperature of the commonly used Al-Si contacts in CMOS chips. Modern CMOS devices with titanium silicide, tantalum nitride, nickel silicide¹⁰ and other barrier materials between aluminum and silicon can be heated to higher temperatures. Nevertheless, exposing the CMOS chips to a temperature of 550 $^\circ\text{C}$ required for CNT growth is undesirable, thereby making the CNT growth on the surface of CMOS chips a major integration challenge. Shulaker *et al.*¹¹ show a complex, thermal release tape process for transferring CNTs from one substrate to another. This method is not suitable for mechanically suspended devices such as MEMS-based microbolometer FPAs.

Here we demonstrate a spatially-localized Joule heating technique, warming up only the bolometer membrane, for Fe-based catalytic CNT growth on the surface of the bolometer membrane while the rest of the substrate remains at room temperature. This method enables the integration of a highly efficient, IR-absorbing CNT layer onto existing monolithic CMOS FPA imagers.

Results and Discussion

Microbolometer design and fabrication

Using the Nanolithography Toolbox¹², we designed $40\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$ microbolometer membranes⁴ using a fabrication flow outlined in Fig. 1. Microbolometers, with an embedded Ti resistive temperature detector (RTD) and Fe layer for catalytic CNT growth, were fabricated using conventional Si bulk-micromachining techniques. Prior to membrane release, we measured the RTD resistance and the temperature coefficient of resistance (α) using a probe station with a heated wafer chuck. The corresponding measured ambient temperature resistance (R_0) and α values were $(7.726 \pm 0.250)\text{ k}\Omega$ and $(0.53 \pm 0.01)\text{ mK}^{-1}$, both represent (mean $\pm$ standard deviation measured from), respectively. The experimental procedure and uncertainties are described in the supplementary section 1. Membranes were then released by removing the underlying Si using XeF_2 vapors. Subsequently, CNT growth was carried out on individual chips.

Microbolometer characterization

Following membrane release, microbolometer chips were mounted onto a leadless chip carrier with 68 pads and electrically connected with gold wires using wire-bonding. Packaged bolometer devices were then placed into a vacuum chamber with a Ge window. Using a method described by Gu *et. al.*¹³, at a pressure of $\approx 7.7 \times 10^{-4}\text{ Pa}$ and an applied voltage amplitude (V_b) of $\approx 0.6\text{ V}$ with known values of R_0 and α , we determined the thermal capacitance (H), G and thermal time constant ($\tau = H/G$). Our measurements over three sets of bolometer devices show $H = (3.113 \pm 0.009)\text{ nJ}\cdot\text{K}^{-1}$, $G = (160.9 \pm 2.7)\text{ nW}\cdot\text{K}^{-1}$ and $\tau = (19.35 \pm 0.34)\text{ ms}$ (mean $\pm$ standard deviation). The experimental procedure and uncertainties are described in the supplementary section 2. At a constant pressure of $\approx 5\text{ Pa}$ and ambient temperature of $\approx 25\text{ }^\circ\text{C}$, the convective heat transfer and radiation loss are negligible and consequently, G is solely determined by the thermal conduction of the microbolometer legs (P_C)¹⁴. Once the microbolometer membrane warms up by the dissipated Joule heat (P_J), the radiation heat loss (P_R), based on the Stefan-Boltzmann law, cannot be neglected. The amplitude of P_J , distributed between P_R and P_C , is given by:

$$P_J = P_R + P_C = A \cdot \varepsilon \cdot \sigma \cdot T^4 + G \cdot \Delta T, \quad (2)$$

where $A = 2 \cdot a^2$ is the top and bottom area of the square microbolometer membrane of length a , ε is the emissivity of the microbolometer membrane, σ is the Stefan-Boltzmann constant, T is the thermodynamic temperature, and ΔT is the temperature difference between the microbolometer membrane and the substrate chip. We measured the bolometer response to a square wave pulse¹³ over a range of V_b values (Fig. S4A in supplementary section 3). In the vicinity of $V_b = 0$, where self-heating effects are neglected, our calculations show $G = (180.4 \pm 1.2)\text{ nW}\cdot\text{K}^{-1}$, $H = (3.602 \pm 0.024)\text{ nJ}\cdot\text{K}^{-1}$ and $\tau = (19.96 \pm 0.02)\text{ ms}$ (all are mean $\pm$ fitting error). Here and below, the fitting error corresponds to one standard deviation of the least-squares fit parameters. The values were in good agreement with the ones determined at $V_b \approx 0.6\text{ V}$. Collectively this data shows that self-heating plays a minor role in the bolometer performance.

Monitoring of CNT growth

The packaged bolometer devices were then placed into a vacuum chamber equipped with a glass window, tubes for gas and vacuum connections, and an electrical feedthrough, as schematically shown in Fig. 2A. The chamber was then placed under an optical microscope equipped with ≈ 9 mm working distance, $50\times$ objective with a numerical aperture (NA) of 0.55. The ≈ 7 mm distance between the bolometer membrane and the glass window allowed for high-resolution, *in situ* observation of the subsequent CNT growth processes. Thermal conditioning of the catalytic layer was accomplished by heating the microbolometer using $P_J \approx 200 \mu\text{W}$ in the 5 % H_2 + 95 % N_2 forming gas (FG) environment for ≈ 15 min. To determine the Joule heat threshold required for growth, we increased P_J until the onset of CNT growth. Further increase of P_J revealed an upper limit of $750 \mu\text{W}$ above which the bolometer membrane was physically damaged from the excessive power dissipation. To circumvent the membrane damage, P_J was set to $650 \mu\text{W}$. Using a closed-loop feedback configuration, P_J was maintained by the controlling voltage V_{BOL} while measuring the current I_{BOL} through the microbolometer resistor. During CNT growth, we maintained a chamber pressure of ≈ 5 Pa by adjusting partial pressures of individual gases at ≈ 1.5 Pa and ≈ 3.5 Pa for FG and C_2H_2 , respectively. Under the above conditions, the CNT thickness was controlled by growth time. Following CNT growth, surface passivation was not carried out. Fig. 2B and 2C show optical micrographs of the microbolometer membrane before and after growth, at ≈ 65 % of the field of view, respectively. The typical microbolometer membrane with grown CNTs is shown in Fig. 3A and 3B. A video (Figure 2D) (Multimedia view) shows real time CNT growth on the surface of the bolometer membrane.

We used finite element modelling (FEM) to show the temperature distribution within the thermally isolated membrane and the surrounding substrate. For the computation, we considered a silicon volume of $160 \mu\text{m} \times 180 \mu\text{m} \times 75 \mu\text{m}$ with a suspended bolometer membrane and materials of dimensions resembling the fabricated devices. We used 20-node thermal solid elements for the Si substrate and 10-node tetrahedral thermal solid elements for Ti and SiO_2 layers. The initial boundary condition for the Si substrate was set to 25°C . Directly following, we applied a voltage of 0.8 V between the ends of the two Ti metal traces. The FEM results (Figures 3C and 3D) show heat concentration within the suspended membrane with the substrate at approximately room temperature.

The measured photocurrent (I_p) from the silicon photodiode during the CNT growth was related to the emitted radiation from the heated membrane (Fig. 4A, supplementary section 5). During the measurements, the microscope light source was turned off. I_p was converted into a voltage (V_p) using a current preamplifier with an active low-pass filter. The amplitude of V_p was monitored using an oscilloscope. I_p as function of time (t) during the growth phase, initiating at $t \approx 112$ s, can be approximated by a first order exponential decay in combination with a linear decay:

$$I_p = I_0 + I_1 \cdot e^{-\frac{t-t_0}{\tau_e}} + I_2 \cdot t, \quad (3)$$

where I_0 is the steady state photocurrent offset, I_1 is the maximum photocurrent, t_0 is time at the onset of amplitude decay (≈ 112 s in Fig. 4A), τ_e is the emission time constant, and I_2 is the coefficient of linear I_p decay. Our measurements show values of $\tau_e = (34.91 \pm 1.26)$ s and $I_2 = (-15.94 \pm 2.02)$ fA·s⁻¹, both values are (mean $\pm$ one standard deviation measured from 3 devices) (Fig. 4A). The uncertainties are calculated from the functional fitting error using Eq. (3). Details of the measurement results are in the supplementary section 4. The value of τ_e can serve as a guide to minimize the CNT growth time with saturated absorbance value.

Since the amplitude of I_p is proportional to P_J , the exponential decay of the I_p as a function of t can be derived from Eq. (2), while accounting for the geometric change of the radiation emitting area during CNT growth. The G value of a microbolometer is determined by the cross-sectional areas, length and thermal conductivity of the two microbolometer legs. Since the CNT layer was grown from the lithographically-defined catalyst spanning the square shaped microbolometer membrane with an area of A (see Fig. 1G and 1H), the value of G remains constant during CNT growth.

During the growth, since P_J was held constant at ≈ 650 μ W, terms A and G in Eq. (2) can be also considered as constant. Consequently, the CNT layer on the surface of the membrane increased ϵ and decreased T . With increasing ϵ , the membrane emits radiation in all directions thereby lowering the temperature. Consequently, the power emitted per unit area of the microbolometer membrane decreases (supplementary section 5). Measured resistance during the CNT growth allowed a qualitative determination of the microbolometer temperature change T :

$$R_b = \frac{V_{\text{BOL}}}{I_{\text{BOL}}}; R_b = R_0(1 + \alpha \cdot \Delta T); \text{ and } \Delta T = \frac{1}{\alpha} \left(\frac{V_{\text{BOL}}^2}{P_J \cdot R_0} - 1 \right), \quad (4)$$

where R_0 and α are the corresponding ambient resistance at $T \approx 298$ K and temperature coefficient of resistance of the temperature sensor, respectively. The T amplitude dropped once P_J reached an amplitude of ≈ 650 μ W at the onset of CNT growth.

Above we assumed a negligible emission contribution from the membrane sidewalls, and considered the source of emission solely from A . However, during CNT growth, the total surface area as a function of the CNT layer thickness (t_c) increases by a factor of $4 \cdot a \cdot t_c$ (supplementary section 6) while the sidewall emission increases with t_c . This increase is not negligible and consequently results in a decrease of I_p at a rate of (-15.70 ± 1.38) fA·s⁻¹ (mean $\pm$ fitting error) (Fig. 4A).

Using a ≈ 100 W tungsten lamp, we illuminated the bolometer membrane and measured the reflectance during CNT growth (Fig. 4B and supplementary section 7). The dynamics of the reflection-based experiment differed from the emissivity measurement. Once the CNT growth initiates at $P_J \approx 420$ μ W, the amplitude of light reflected from the membrane decreased following an exponential decay of the first order with time constant $\tau_r = (13.44 \pm 0.07)$ s (mean $\pm$ one standard deviation from 3 devices). The faster τ_r , in comparison τ_e ,

shows that the related reflection from the membrane in visible spectrum of electromagnetic radiation is sensitive to small changes in surface properties, whereas a much thicker layer of CNTs is required to cause significant changes to τ_e ⁶.

Inserting the parameters obtained from the above microbolometer characterization into Eq. (2) allowed us to calculate the amplitude of P_j as a function temperature, without the CNT layer and for various CNT thickness values up to 30 μm (Fig. 5A). In our calculations, we used $\epsilon_{\text{SiO}_2} = 0.48$ and $\epsilon_{\text{CNT}} = 1$ for the emissivity of membranes without⁴ and with^{11,15} CNTs, respectively. Furthermore, the area of the CNT membrane was $A = 2 \cdot a^2 + 4 \cdot a \cdot t_c$ (supplementary section 6). The results in Fig. 5A show that the P_j amplitude required to heat up bolometer membrane without and with the CNT layer to the same value of T increases with increasing thickness of the CNT layer.

We then calculated the power of emitted radiation $P_{\text{ER}} = b \cdot \epsilon \cdot \sigma \cdot T^4$ from a 1 μm^2 area (b) of the bolometer membrane without CNTs and for various CNT layer thicknesses. Fig. 5B shows a significant emission dependence with respect to the CNT layer thickness.

Experimental data in Fig. 6 show that membranes with CNTs are cooler and emit ≈ 0.23 of the power emitted by membranes without CNTs. Our results further show that the CNT layers increased the value of thermal capacitance H by a factor ≈ 5 , to $(14.83 \pm 0.53) \text{ nJ} \cdot \text{K}^{-1}$ (mean $\pm$ standard deviation, 3 measurements).

CNT layer performance

We placed the bolometer, connected in a balanced Wheatstone bridge configuration, into a vacuum chamber and evaluated the P_{IR} response. The amplitude of P_{IR} was controlled by distance (D) between black body at $T \approx 673.15 \text{ K}$ and bolometer from $D \approx (59.5, 74.5, 89.5, 104.5, \text{ and } 119.5) \text{ mm}$. The P_{IR} was estimated using:⁴

$$P_{\text{IR}} = \alpha^2 \cdot \epsilon_{\text{bb}} \cdot \tau_{\text{F}} \cdot M \left[\frac{\left(\frac{d}{2}\right)^2}{D^2 + \left(\frac{d}{2}\right)^2} \right], \quad (5)$$

where ϵ_{bb} is the emission of black body with amplitude of ≈ 0.95 (manufacturer's datasheet value), τ_{F} is the average experimentally determined transmittance of the Ge window with value of $\tau_{\text{F}} \approx 0.76$, M is the integrated radiant exitance of black body (supplementary section 8) according to Planck's radiation law with an amplitude of $\approx 2588 \text{ W} \cdot \text{m}^{-2}$ and $d \approx 10.5 \text{ mm}$ is the diameter of the black body radiation source. The value of τ_{F} was determined by a ratio of an output signal of a commercial microbolometer based IR camera with and without the Ge window. The microbolometer responsivity to IR radiation ($\mathfrak{R}_{\text{IR}}$) is defined as:

$$\mathfrak{R}_{\text{IR}} = \frac{\Delta V_{\text{out}}}{P_{\text{IR}}}. \quad (6)$$

Our results show that, by adding the CNT absorbing layer, the $\mathcal{R}_{\text{IR}}$ increased by a factor of (2.3 ± 0.1) (mean $\pm$ fitting error) (Fig. 7).

Conclusions

Our work presented here, for the first time demonstrates CNT growth on the surface of suspended microbolometer membranes while keeping the device substrate at room temperature. By taking advantage of the thermally isolated nature of the released microbolometer membrane, the developed CMOS fabrication compatible method allows for integration of IR absorbing CNTs with variety of active device architectures including FPAs. Our results show ≈ 2.3 fold IR responsivity increase with grown CNT absorbers and reached the $\mathcal{R}_{\text{IR}}$ of $(16.35 \pm 0.48) \text{ kV} \cdot \text{W}^{-1}$. Furthermore, the IR absorption near unity is determined solely by the CNT layer regardless of the membrane material and thickness, cavity and underlying IR reflector. The promising growth technique of highly absorbing CNT layers using spatially localized heating on the surface of suspended membranes opens opportunities for complex integration of these absorbing layers for efficient IR imaging and FPA emission applications.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Fabrication process flow of the MEMS based microbolometer. (A) Deposition of $\approx 0.25 \mu\text{m}$ plasma enhanced CVD (PECVD) SiO_2 on the Si substrate. (B) Lithographic definition of $\approx 0.9 \mu\text{m}$ thick Al bond pads. (C) $\approx 30 \text{ nm}$ sputter deposited Ti temperature sensor definition using optical lithography and reactive ion etching. (D) Deposition of $\approx 0.25 \mu\text{m}$ PECVD SiO_2 for protection of metal layers. (E) SiO_2 patterning to create access to bonding pads and etch holes for the microbolometer membrane release. (F) Deposition of the catalytic Fe layer using a photoresist liftoff process. (G) Cross section of a microbolometer chip following microbolometer membrane release using XeF_2 vapors. (H) Catalytic CNT growth on the surface of the membrane.

Fig. 2.

(A) Schematic illustration of the experimental setup. The microbolometer was placed into a vacuum chamber with an inlet for gas delivery and a pumping port. Gas flow was controlled by needle valves (NV). Chamber evacuation was accomplished using a combination of a turbo molecular pump (TMP) with a backing dry vacuum pump (DP). Using an optical microscope with a $50\times$ objective lens (OL), the optical window flange allowed for real-time monitoring of the CNT growth process. Reflectance measurements during CNT growth were accomplished using a tungsten lamp (TL) in conjunction with a beam splitter (BS) to illuminate the microbolometer membrane. Emission and reflection during CNT growth were measured using a silicon photodiode (PD). The I_p was converted to a voltage using a current preamplifier (Amp) that was monitored using an oscilloscope (Osc). The P_j amplitude dissipated in the microbolometer membrane was set using a closed-loop feedback system by controlling the amplitude of V_{BOL} while measuring I_{BOL} and keeping the P_j at a predetermined value. Optical micrographs of a microbolometer (B) before and (C) after the CNT growth. The scale bars in (B), (C) and (D) represent a length of $\approx 40\ \mu\text{m}$. (D) A video (Multimedia view) showing a real-time the CNT growth at the bolometer membrane captured with microscope equipped with $50\times$ objective lens.

Fig. 3.

Scanning electron micrographs of fabricated microbolometer showing (A) a thermally isolated, undercut microbolometer membrane following CNT layer growth. (B) Zoomed-in view of the CNTs near the membrane edge. The scale bars in (A) and (B) represent lengths of $\approx 20 \mu\text{m}$ and $\approx 5 \mu\text{m}$, respectively. FEM analysis with (C) perspective and (D) top-down views of the temperature distribution within the structure. The heat is localized within the suspended, membrane region with the surrounding Si substrate at 25°C . The scale bars in (C) and (D) represent lengths of $\approx 40 \mu\text{m}$. The annotations in (D) represent temperatures at various locations, denoted by the corresponding arrows, along the structure.

Fig. 4.

(A) Typical optical emission from the microbolometer membrane as a function of t during CNT growth. P_j was gradually increased at a rate of $\approx 8 \mu\text{W}\cdot\text{s}^{-1}$ up to $650 \mu\text{W}$. At $t \approx 53 \text{ s}$ we observed light emission from the membrane. CNT growth, initiating at $t \approx 112 \text{ s}$ with $P_j \approx 650 \mu\text{W}$, increased the microbolometer emissivity and thereby lowered the microbolometer membrane temperature. At $t \approx 850 \text{ s}$, heating was switched off ($P_j = 0 \text{ W}$) and the CNT growth ceased. Directly following, the light emission quickly decayed to zero. We determined the value of τ_e using Eq. (3) as $(32.03 \pm 0.82) \text{ s}$ (mean $\pm$ fitting error). Solid line represents a first-order exponential decay functional fit. (B) Under similar conditions, we measured the optical reflection from the microbolometer. At $t \approx 40 \text{ s}$, an increase from a steady state of $P_j \approx 90 \mu\text{W}$ caused the membrane reflectivity to drop. The CNT growth initiated at $t \approx 86.5 \text{ s}$ with $P_j \approx 420 \mu\text{W}$. The newly grown CNT layer lowered the membrane reflection with a time constant $\tau_r = (13.44 \pm 0.07) \text{ s}$ (mean $\pm$ fitting error). The maximum $P_j \approx 650 \mu\text{W}$ occurred at $t \approx 96 \text{ s}$. At $t \approx 250 \text{ s}$, the heating was switched off, following which the reflection amplitude changed marginally. Solid line represents a first-order exponential decay functional fit.

Fig. 5.

(A) Calculated values of dissipated Joule heat P_J as function of T for microbolometer without CNTs (thick black line) and for various CNT thickness values. The CNT membranes require a larger P_J to remain at a distinct T . (b) Calculated values of P_{ER} as a function of P_J for microbolometers without CNTs (thick black line) and for various t_c values.

Fig. 6.

(A) Measured light emission amplitude from bare (black squares) and CNT covered (red circles) microbolometer membrane as a function of dissipated P_J . The two insets are scanning electron micrographs of microbolometers with and without the CNT layer. Scale bars represent 40 μm. Solid lines represent a 4th order polynomial curve fitting with cubic coefficient set to zero. The radiation power amplitude of the microbolometer with the CNT is ≈ 0.23 of the one without. Filled in markers are average values and vertical bars represent one standard deviation resulting from repeated measurements across a device. (B) Optical micrograph showing light emission from the membrane at $P_J \approx 650$ μW. The scale bar represents 40 μm.

Fig. 7.

Wheatstone bridge output voltage change V_{OUT} as a function of incident P_{IR} for microbolometer with (red circles) and without (black squares) a CNT layer. The amplitude of P_{IR} was calculated from black body – bolometer distance as per Eq. (5) and supplementary section 8. The bridge was biased with a square wave pulse of amplitude ≈ 0.6 V and duration ≈ 200 ms. The V_{OUT} amplitude was captured at $t \approx 200$ ms. Using linear regression, the microbolometer $\mathcal{R}_{IR}$ with and without CNT was $(16.35 \pm 0.48) \text{ kV} \cdot \text{W}^{-1}$ and $(7.08 \pm 0.24) \text{ kV} \cdot \text{W}^{-1}$, both (mean $\pm$ standard deviation, across 3 measurement), respectively. Filled in markers are average values and vertical bars represent one standard deviation resulting from repeated measurements across three devices. Overall, with CNTs, $\mathcal{R}_{IR}$ increases by a factor of (2.3 ± 0.1) (mean $\pm$ fitting error).