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High-Impedance Surfaces for Above-IC Integration of Cooled Bolometer Arrays at the 350- μm Wavelength

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Abstract High-impedance surfaces (HIS) are investigated here for the above-IC integration of sub-millimeter-wave (350 μm here) detectors on CMOS electronics using standard thin film manufacturing processes and materials. We demonstrate theoretically and experimentally the efficient optical absorption of a resistive dipole array above an HIS at cryogenic temperature. More specifically, an absorption above 78% in linear polarization is obtained over a bandwidth of 100 μm around a center wavelength of 350 μm . These results confirm the promising performances of HIS structures in the perspective of future polarimetric bolometers in terms of absorption efficiency, bandwidth and cross-polarization discrimination.

Keywords millimeter waves • sub-millimeter waves • bolometer • high-impedance surfaces • superconductors • microfabrication

1 Introduction

Silicon bolometers cooled at 50-300 mK have been demonstrated as high-performance detectors for astrophysics in several space and ground-based observatories [1][2]. In the frame of the SPICA space observatory project, bolometer detector arrays operating in the 100- μm band have been developed for the B-BOP polarimetric imaging instrument [3][4].

These detectors are integrated on a CMOS read-out integrated circuit (ROIC) for low-noise amplification and signal multiplexing (Fig. 1 *left*). This above-IC (integrated circuit) integration scheme, i.e. microfabrication on 200-

mm CMOS ROIC wafers, does not allow thick film processes, which would be normally required to scale the detector design to longer wavelengths since these detectors rely on a quarter-wavelength optical cavity between the ROIC and the optical absorbers.

In this work, High-Impedance Surfaces (HIS) are investigated and demonstrated to enable the above-IC integration of detectors designed for the 350- μm (λ_0) band with an optical cavity equivalent to a quarter-wavelength cavity but no thicker than 14 μm , i.e. less than $\lambda_0/25$ (Fig. 1 *right*).

Prototypes have been designed, manufactured and characterized in optical absorption at room temperature and 1.6 K to demonstrate the feasibility and absorption performance in the targeted wavelength and temperature range.

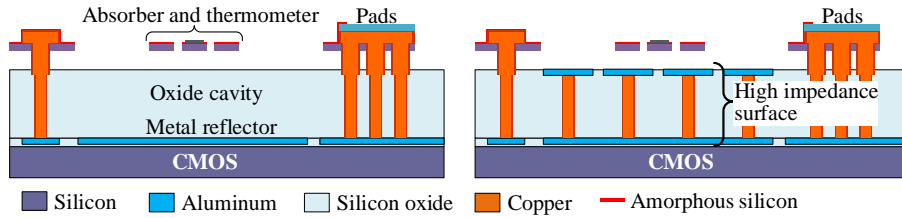


Fig. 1 Bolometer detector cross-sections for the 100- μm band (*left*) and for the 350- μm band with a high-impedance surface (*right*). (Color figure online)

2 High-Impedance Surfaces

High-impedance surfaces, also called Artificial Magnetic Conductors (AMC), are quasi-planar periodic structures with sub-wavelength period and thickness exhibiting a complex reflection coefficient close to +1 in a given frequency band [5][6]. They have been widely investigated in the context of millimeter-wave integrated antennas and terahertz uncooled bolometers [7][8]. A well-known design is used here in the form of an array of square metallic patches above a ground plane with vertical vias connecting the center of each patch to the ground plane (Fig. 2) [9]. In this work, the metal patches are made of Ti/TiN/AlSi (10/40/300 nm) with a size of $32.9 \times 32.9 \mu\text{m}$ and a period of $37.5 \mu\text{m}$. The vias have a diameter of $3 \mu\text{m}$ and are made of copper electroplated on a thin (20 nm) seed layer of TiN. The ground plane, or reflector, is made of Ti/AlCu/Ti/TiN (50/440/10/40 nm). The dielectric separating the patches and the ground plane is silicon dioxide with a thickness of $11 \mu\text{m}$.

In this work, electromagnetic simulations are performed with Ansys-HFSS (Finite-Element method) with estimated material parameters either at room temperature or at cryogenic temperatures ($\sim 1.6 \text{ K}$). While the materials mentioned above include some superconducting metals, the operating

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frequency (0.75-1 THz) and temperature (1.6 K for characterization, 100-300 mK for future detectors) are far enough from their gap frequency and transition temperature so that their electrical conductivity at cryogenic temperatures is considered close to their DC conductivity just above their transition temperature.

The simulated reflection coefficient of the HIS under normal incidence exhibits a resonance at 258 μm (1.16 THz) with a reflection magnitude higher than 0.93 at low temperature (Fig. 2). This spectral response is characteristic of an equivalent LC parallel circuit.

Fabricated prototypes have been characterized in absorption at room temperature using a Time-Domain Spectrometer (TDS) and at low temperature using a Fourier-Transform Spectrometer (FTS) in reflection mode. In both cases, measurements are made with a linearly-polarized beam with an incidence of 10-12.5° and the instrument is calibrated with an aluminum mirror made from the same metal stack as the reflector layer of the samples.

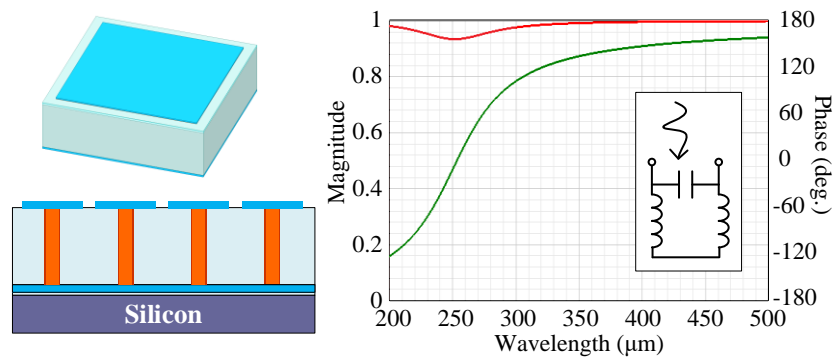


Fig. 2 Cross-section of the HIS (*bottom left*), 3D view of a unit cell (*top left*), simulated reflection phase and magnitude (normal incidence, low temperature) (*right*) (inset: electrical equivalent circuit) (Color figure online).

The simulation under normal incidence at room temperature exhibits a broad absorption band centered at 260 μm with a maximum of about 40%. Under oblique incidence and in TM (Transverse Magnetic) polarization (electric field in the incidence plane and collinear to the vias), an additional sharp resonance appears at 270 μm with a height dependent on the incidence angle (Fig. 3 *left*). For an incidence of 10°, the simulated absorption peaks at about 80% and is close to the experimental response. This spurious resonance is linked to the vias, which couple to the incident electric field with a series LC resonance. In contrast, this mode is not excited in TE (transverse electric) polarization since the incident electric field is perpendicular to the vias.

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Instead, the HIS exhibits a broad absorption mode of 35-40% around its main resonance wavelength (250-270 μm).

At low temperature, the spurious resonance in TM polarization at 270 μm remains and is slightly sharper due to the higher conductivity of metals and lower losses in the dielectric (Fig. 3 *right*). The main resonance of the HIS is clearly visible in TE polarization at 250 μm with a magnitude of 20-25% in experiment and 15% in simulation. More experimental and simulation work are required to investigate the origin of this discrepancy, which may be due to an underestimation of the materials losses or the calibration of the instrument in this band. It is important to note at this stage the low absorption (< 10%) in the 300-400 μm band targeted for our future detector.

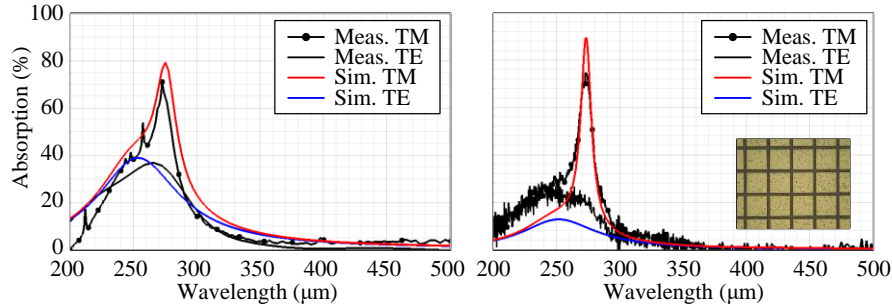


Fig. 3 Absorption of the HIS at room temperature (*left*) and 1.6 K (*right*); simulations and measurements are given both for TM and TE mode (inset: photograph of the HIS sample showing 4 \times 3 metal patches). (Color figure online).

3 Absorbing dipoles over HIS for polarimetric detectors

A proof-of-concept of our future detector has been designed in the form of an array of absorbing dipoles fabricated above the HIS presented in section 2. The dipoles are separated from the HIS by a thick (4.5 μm) silicon oxide layer. As compared to an actual detector such as described in section 1, these prototypes differ slightly by the materials located between the absorbers and the HIS, but with negligible differences on electromagnetic properties.

The dipoles are made of Ti/TiN (50/50 nm) and passivated by a thin (50 nm) amorphous silicon layer (Fig. 4). The dipoles size (84 \times 8 μm^2), period (150 \times 150 μm^2) and resistivity were optimized for a maximum absorption at 350 μm wavelength. The selection of the dipoles metal is critical in getting the appropriate resistivity at low temperature. Preliminary trials (full sheet deposition) of several metals and bilayer combinations have been characterized at low temperature [10]. The selected Ti/TiN bilayer exhibits a

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square resistivity of $8.9 \Omega/\square$ at room temperature, $2.1\text{-}2.9 \Omega/\square$ above 4 K and a transition temperature of 3.2-4 K.

Fig. 4 *right* shows the simulated and measured absorption for the co-polar and cross-polar polarizations. Simulations are provided both for the total absorption and the absorption in the dipoles only (red and blue plots with symbols). The simulation assumes $9 \Omega/\square$ of resistivity for the dipoles metal. A good agreement is obtained between the simulated and measured total absorption in terms of center wavelength and maximum absorption. The bandwidth is slightly overestimated in the model. It is worth to note that the cross-polar total absorption is significant ($\sim 40\%$) due to the absorption in the HIS. In addition, the spurious TM mode resonance at $\sim 270 \mu\text{m}$ is clearly visible on the cross-polarization component, which corresponds to the TM polarization in our set-up, but appears also slightly on the co-polarization component (TE polarization), which indicates possibly a coupling between the dipoles and this resonance mode.

The simulated absorption in the dipoles reaches 74% at 330-350 μm for the co-polarized component and is less than 2% in cross-polarization. This cross-polarization level should be taken as an estimation as the accuracy of the simulation is limited by available computer resources.

Fig. 5 shows the simulated and measured absorption at low temperature (1.6 K) for this prototype. The resistivity of the absorbing dipoles was set to $4 \Omega/\square$ in the simulation model in order to fit the measurements and this value is in reasonable agreement with the expected value ($\sim 3 \Omega/\square$) mentioned above. Again, a good agreement is reached between simulation and measurements. The cross-polar absorption is significantly reduced ($\sim 20\text{-}25\%$) as compared to the room temperature measurement and the spurious absorption resonance at 270 μm is clearly visible.

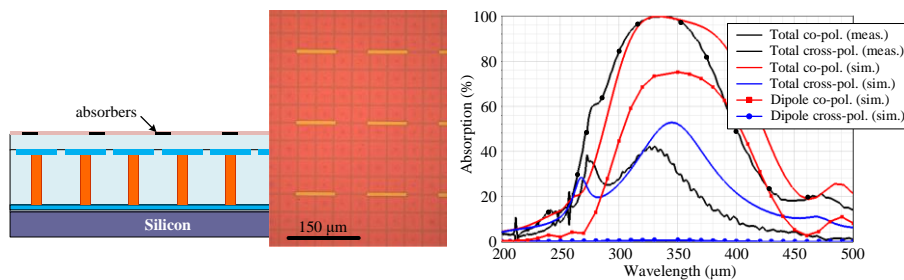


Fig. 4 Cross-section of the prototype with dipole absorbers over the HIS (*left*), top view photograph (*middle*), simulation and measurement of absorption at room temperature (*right*) (Color figure online).

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Fig. 5 (*right*) compares the total absorption to the dipole absorption, showing that the absorption takes place essentially in the dipoles in the 280-400 μm band. The dipole absorption is higher than 50% at 285-400 μm and higher than 78% at 295-385 μm . Moreover, the cross-polarization component remains very low, less than 1%. These results provide solid evidences of the performances of this structure for future polarimetric bolometers in terms of absorption efficiency, bandwidth and cross-polarization discrimination.

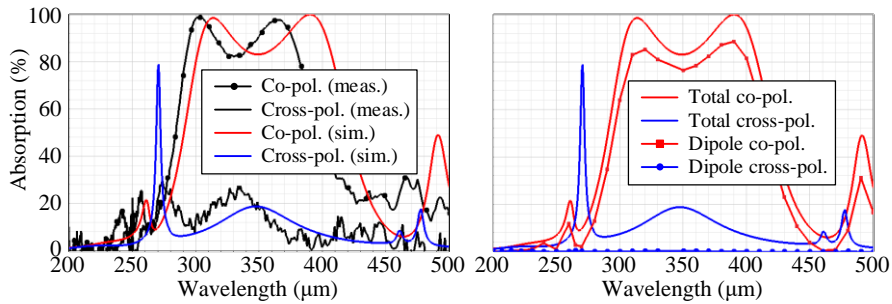


Fig. 5 Simulation (absorber resistivity: $4 \Omega/\square$) and measurement of the total absorption at 1.6 K (*left*), simulation of the absorption in the dipoles compared to the total absorption (*right*) (Color figure online).

4 Conclusion

The development of polarimetric detector arrays in sub-millimeter bands is of high interest for future cameras, such as the B-BOP instrument developed for the SPICA observatory and dedicated to the study of the magnetic field in various astrophysical environments. One of the challenges is the integration of such detectors on read-out CMOS electronics using above-IC technologies, in particular for long wavelengths, which would require very thick layers.

In this work, the concept of high-impedance surfaces was demonstrated for the integration of polarized absorbers at a distance lower than $\lambda_0/25$ from a reflector. The simulation and measurements of absorption by resistive dipoles demonstrate the feasibility of efficient absorption (above 78%) in linear polarization over a bandwidth of 100 μm around a center wavelength of 350 μm .

Future work will focus on the development of actual bolometer detectors using this concept and based on the detector technology developed for the B-BOP instrument.

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