Substrate and Device Pattern Dependence of the Thermal Crosstalk in Y $Ba_2Cu_3O_{7-\delta}$ Transition Edge Bolometer Arrays

Ali Bozbey, *Student Member, IEEE*, Mehdi Fardmanesh, *Senior Member, IEEE*, Juergen Schubert, and Marko Banzet

***Abstract*—Using $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films, pulsed laser deposited on 1-mm-thick $LaAlO_3$ or $SrTiO_3$ substrates, we made 4×1 pixel arrays of transition edge bolometers with separations between neighboring pixels ranging from 40 μm to 170 μm for testing purposes. We investigated the effects of the YBCO film thickness (200 and 400 nm), substrate material, and back-etching of the substrate, on the crosstalk between the pixels of the arrays. The investigation was based on the analysis of the voltage response of the dc current biased bolometers versus the modulation frequency of a near-infrared laser source. We observed that the bolometer arrays made of 400-nm-thick films had less interpixel thermal crosstalk than the 200-nm-thick films. The effect of substrate thickness on the response of the pixels was investigated by up to 500 μm back-etching of the substrates. The bolometers made on back-etched $LaAlO_3$ substrates had anomalous crosstalk response behavior, which was effective at higher modulation frequencies. In addition, we present an analytical thermal model for explaining the observed effects of the thermal crosstalk on the response characteristics of the pixels of the arrays. We report the measured response and the anticipated thermal crosstalk of the characterized bolometers'. We describe the responses based on the thermal models and discrepancies from the model's predictions.**

***Index Terms*—Bolometer array, infrared detector, Superconductivity, thermal conductivity, thermal crosstalk.**

I. Introduction

CROSSTALK studies in $YBa_2Cu_3O_{7-\delta}$ (YBCO) bolometer arrays are essential for specific application-oriented optimization purposes as well as for understanding the physics of the bolometers operation. As the number of pixels in an array increases and the size of the pixels decrease, the thermal crosstalk becomes a limiting factor in the design of transition edge bolometer arrays. Recently a number of studies have reported on the crosstalk in the bolometer arrays [1]–[3]. We have previously presented and analyzed the effects of temperature at transition and separation between the pixels on the crosstalk in the same type of bolometer arrays [4] and proposed a related analytical thermal model [5]. It has already been shown that the thermal diffusion length (L_f) is one of the key parameters that helps in understanding the thermal crosstalk-based response between the pixels of the arrays. L_f represents the characteristic penetration depth of temperature variation into the substrate and has been formulated as [4], [6]

$$L_f = \sqrt{\frac{D}{\pi f}} \tag{1}$$

where f is the modulation frequency, $D = k_s/c_s$ is the thermal diffusivity of the substrate material, and k_s and c_s are the thermal conductivity and specific heat of the substrate materials, respectively. The crosstalk response is closely related to the frequency-dependent thermal diffusion length. As the distance between pixels increases to a value greater than the thermal diffusion length at the operating modulation frequency, the effects of the crosstalk on the responses ceases and the response becomes a complex of various parameters, as explained in Section III.

In previous studies, [4], [7] we operated the bolometers at different bias points of their superconducting transitions of $T_{c-\mathrm{zero}}, T_c$, and $T_{c-\mathrm{onset}}$ and reported the effect of temperature on crosstalk between the pixels of the studied YBCO bolometer arrays. We observed that the sense pixels (A, C, and D) of an array, shown in Fig. 1 had a temperature-dependent crosstalk response through the superconductivity transition. However, we observed that the response of the radiation-absorbing source-pixel B shown in Fig. 1 did not show much temperature dependence [4]. This has been interpreted to be due to the dominant thermal conductance through the gold layer on the contact paths of the studied bolometers. Thus, the temperature-dependent response of the pixels A, C, and D in Fig. 1 were associated to be mainly caused by the superconductivity transition-dependent crosstalk between the pixels; the mechanism behind this was investigated in [4].

In this paper, we biased the bolometers at the middle of the transition temperature of T_c; we report a comprehensive investigation of the effects of the dimensions and physical parameters of the bolometers on the crosstalk between them. We also utilize an analytical thermal model, which is mainly based on lateral heat propagation in the substrate and the single pixel bolometer response. The details of the thermal model are presented elsewhere, [5]; in this paper we focus mainly on various

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A. Bozbey is with the Electrical and Electronics Engineering Department, Bilkent University, Ankara 06800, Turkey (e-mail: bozbey@ieee.org).

M. Fardmanesh is with the Electrical and Electronics Engineering Department, Bilkent University, Ankara 06800, Turkey and also with the Electrical Engineering Department, Sharif University of Technology, Tehran, Iran (e-mail: fardmanesh@ee.bilkent.edu.tr).

J. Schubert and M. Banzet are with the ISG1-IT and Center of Nanoelectronic Systems for Information Technology, Forschungszentrum Juelich GmbH, D-52425 Juelich, Germany

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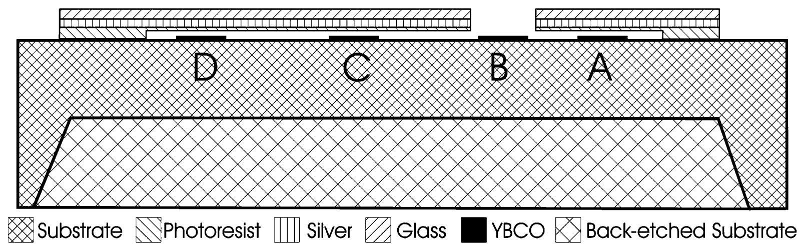

Fig. 1. Side view of the test bolometer array. The "source pixel" B, which is exposed to the laser radiation and "sense pixels" A, C and D which are blocked by the reflecting mask.

aspects of the anticipated thermal-crosstalk-based response of the sense and source pixels. To support our qualitative conclusions, in Section IV, we show the theoretical fittings based on the thermal model.

II. Sample Preparation and Experimental Setup

The crosstalk study was made possible through the illumination of the radiation absorbing source-pixels (pixel B in Fig. 1) and measuring the voltage response of the dc current biased blocked sense-pixels (A, C, and D in Fig. 1) in the same array. We prepared 4×1 bolometer arrays made of 200- and 400-nm-thick YBCO films deposited by pulsed laser deposition (PLD) on (001) crystalline $SrTiO_3$ and $LaAlO_3$ substrates. The illuminated pixels in the arrays had an area of 20 μm $\times$ 1 mm and the test neighbor pixels had areas of 20 μm $\times$ 0.75 mm. This was to investigate the thermal coupling or the crosstalk between the bolometers in the form of arrays of long bridges. To observe the effect of back-etching as shown in Fig. 1, we etched the substrates up to 500 μm by mechanical means.

In order to measure the thermal crosstalk between the bolometers in the arrays, it was essential to keep the test bolometers optically isolated from the environment. However, while optically isolating the bolometers, it should be taken into consideration that optically isolating the bolometers does not cause additional thermal coupling artifacts in the arrays. As Fig. 1 shows, the "source-pixel" is illuminated with modulated IR radiation whereas the other three "sense-pixels", are blocked with a free standing reflecting mask. The distances of the sense pixels of A, C, and D, from the source pixel were 40 μm, 60μm, and 170 μm, respectively.

The mask had a 25 μm wide window for illumination of the source pixel and was aligned on top of the bolometer array in a flip-chip configuration. Radiation blocking was achieved in a flip-chip configuration. The reflecting mask was made of a 250-nm-thick sputtered silver layer on 0.1 mm glass so that the IR transmittance was reduced to 1%. This amount of transmittance had little or no effect on the responses at low and mid-modulation frequencies. A thick photoresist layer was spinned and a larger window was opened so that the mask was free-standing on top of the pixels, eliminating any parasitic thermal or electrical contacts that could affect the measurements. The main bias-contact paths as well as the pads of the pixels were coated with a sputtered gold layer that reduced the resistance of the YBCO contact paths at operating temperatures. This ensured that the measured response was due only the bridge areas. In the configuration we used, the thermal conductance of the sputtered gold is much higher than that of the bridge film contact pads. Thus the effects of the bridge film thermal parameters over the response of an individual pixel is negligible. This enables us to focus on the interpixel crosstalk rather than on the response affected by the thermal parameters of the contact pads of individual pixels. This is further explained in Section IV.A. The lengths of the bolometers and the distances between them were chosen so that lateral thermal conductance dominates over longitudinal thermal conductance. We used a lock-in amplifier (Stanford SR 850) to measure the phase and magnitude of the optical response of the current-biased bolometers. As a radiation source, we used electrically modulated fiber coupled IR laser diode with wavelength of 850 nm and 12-mW output power [4]. The laser was electrically modulated by the lock-in amplifier's internal reference output which was considered to be the responses' phase-angle reference. The responses of the bolometers were measured at the critical temperature, T_c, where the maximum IR response was obtained in a modulation frequency range of 1 Hz to 100 kHz limited by the lock-in amplifier. Further details of the samples and experimental setup are presented elsewhere [4].

III. Analytical Modeling of the Crosstalk

To analyze the characteristics of the crosstalk-based response we developed an analytical model based on the fundamental thermal diffusivity equation [4], [5]. Assuming 2-D lateral heat propagation in the substrate, the spatial variation of the response at distance x away from a single pixel bolometer has been formulated as [8], [9]

$$\frac{T(x,f)}{T_0} = \exp\left[-\sqrt{\frac{\pi f}{D}}x\right] \exp\left[-j\sqrt{\frac{\pi f}{D}}x\right] \tag{2}$$

where, D is the thermal diffusivity of the substrate material, f is the modulation frequency; x is the distance from the bolometer, and T/T_o is the normalized spatial and frequency dependent variation of the temperature in the substrate.

Equation (2) assumes that the heat propagates in two dimensions and the responses of the source and the sense pixels are generated and read without any lag caused by the bulk. However, in practice, there is a lag in the response due to the heat capacity of the substrate material. For example, if the single pixel bolometer B in Fig. 1 were illuminated, its response would have the behavior shown in Fig. 2. Since pixel C has similar physical parameters, we assume it will show similar behavior. By combining the heat propagation equation and the expected response

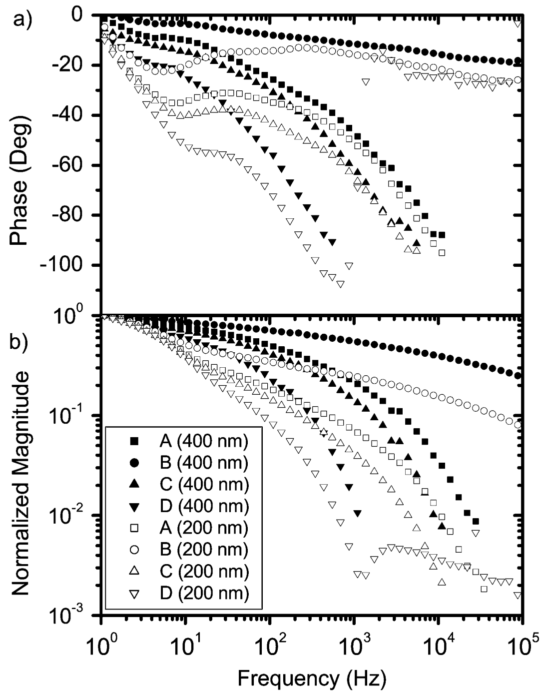

Fig. 2. (a) Phases and (b) magnitudes of 200- and 400-nm-thick bolometers.

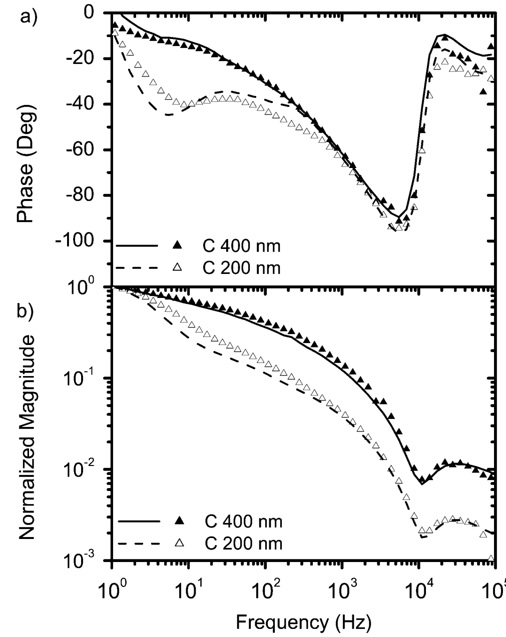

Fig. 3. (a) Phases and (b) magnitudes of 200- and 400-nm-thick bolometers and their fitting curves.

behaviors of pixels B and C, we obtain the following relation for the effects of the crosstalk between the two pixels, B and C

$$r_{v-c}(f) = \exp\left[-(1+j)\sqrt{\frac{\pi f}{D}}x\right] \times (r_{v-B}(f))^{\alpha} + r_{v-B}(f) \times \beta \quad (3)$$

where $r_{v-c}(f)$ is the measured crosstalk-based response of the sense-pixel C, β is the transmittance of the mask, $r_{v-B}(f)$ is the experimental data of pixel B and α is the term for the amount of the crosstalk delay caused by the substrate material and the interfaces. The last term in (3) is the interference term; it refers to the interference in temperature variation caused by the crosstalk response and the leaking laser beam term that is caused by the imperfect blocking of the reflecting mask. In subsequent sections, we will substitute numerical values in (3) and show that there is a very good fit with the experimental results.

IV. Results and Discussion

We have already reported an analysis of the effect of the superconductivity transition and the effect of the separation between pixels on the crosstalk-based response of the YBCO bolometer arrays [4]. In this study, we focus on an analysis of the effects of the substrate material, back-etching of the substrate, and the YBCO film thickness on crosstalk characteristics. We use theoretical fits based on the above modeling to clarify the substrate and pattern dependence of the response behaviors.

The measured crosstalk response of the bolometers is expected to have a lag due to diffusion through the substrate from the surface. Thus the measured response should be a complex quantity with both magnitude and phase as shown in (2). The responses of the sense-pixels are caused by two main sources: 1) the thermal crosstalk between the sense and source pixels and 2) the leaking laser beam due to the imperfect blocking of radiation by the reflecting shadow mask. For example, the response of the sense-pixel D shown in Fig. 2 is thought to be due to crosstalk up to about 700 Hz and mainly due to the direct absorption of the leaking laser beam after about 2.5 kHz; these results confirm the above assumptions. Above a modulation frequency of about 1 kHz, the crosstalk is expected to become negligible and the unblocked leaking input laser power, in the order of 1%, starts to dominate the measured response; this is also predicted from the results in Fig. 2.

A. Effect of the Thickness of the YBCO Film

Based on the measured crosstalk-based response of the 200- and 400-nm-thick YBCO film bolometers with designs as shown in Fig. 2, film thickness is found to affect the response at both low and high modulation frequency ranges. For clarity, the data in Fig. 2 (except for pixel D made of 200-nm-thick YBCO film), are plotted just up to the lowest points where the response starts to be dominated by the direct absorption of the leaking laser beam.

We observed that the phases of the response of the 400-nm-thick film bolometers were smaller and the rates of decrease of magnitude versus frequency were slower than those of the thinner film bolometers. Thus, as shown in Fig. 2, there was more crosstalk between the bolometers made of thick films. We associate this to the ratio between absorption of IR radiation by the YBCO thin film and by the substrate. The 400-nm YBCO films absorb more radiation than the 200-nm films; the lag which is possibly caused by the substrate material, is decreased in the thicker film samples. Fig. 3 shows the curves for pixel C for both the 200- and 400-nm-thick films. The second term in (3), the vertical heat propagation term, plays a larger role in the 400-nm-thick films as explained in [5]. This further confirms our assumption on the effect of the substrate on lag of the crosstalk-based response.

There are two things to consider when fabricating bolometers using thick films. As the cross sectional area through which the current passes increases, electrical resistance decreases, decreasing dR/dT. Second, as the film thickness is increased, beyond 250–300 nm in our PLD system, YBCO film quality decreases and hence the superconductivity transitions of the thick films were less sharp than the thin ones. The loss in the sharpness of the transition with the thicker films might be avoided by optimizing the PLD system, but the inherent decrease in resistance of the film due to the thicker film would result in an overall lower dR/dT, thus degrading the response.

In [10], we investigated the effect of the transition width and film quality of the YBCO films on the response of a single pixel bolometer. We observed that as the transition width increases, the phase dip at low frequencies decreases due to the difference of the lateral thermal conductivity of the YBCO film. However, for the purpose of this study, we have coated the contact paths of the bolometers with gold; this dominated over the thermal parameters of the film and we did not observe the phase dip at low frequencies that happened with the low-quality films in [10]. We can only interpret that the difference in the crosstalk-based phase of the response is not associated with the transition width of the films. Crosstalk characteristics of the bolometers based on thicker films are mainly interpreted to be due to differences in absorbtivities of the 200- and 400-nm YBCO films. Possible effects of structural film quality on the crosstalk has not been investigated.

The decision about the optimal thickness of the YBCO films should take into account the thickness dependence of the film quality, the dimensions of the bolometers, and the targeted range of the operation modulation frequency.

B. Effect of the Substrate Material

The thermal diffusivity of the substrate material is one of the fundamental parameters that affect the thermal crosstalk between the pixels in an array. This is especially true at the low and mid ranges of the modulation frequencies, f_m, where the thermal diffusion length is in the same range as the substrate thickness. In this range, the substrate thermal conductance and thermal capacitance become the dominant parameters that affect the response of the bolometers [11].

Fig. 4 shows the crosstalk response vs. frequency curve of pixel C on $LaAlO_3$ and $SrTiO_3$ substrates. The crosstalk-free f_m for pixel C on $LaAlO_3$ is 21927 Hz whereas the crosstalk-free f_m for pixel C on $SrTiO_3$ substrate is 5850 Hz. Based on these frequencies, the lateral thermal diffusivities of the $LaAlO_3$ and $SrTiO_3$ were calculated to be 0.088 and 0.027 cm^2/s respectively [4], [7].

Fig. 4 shows that the curves based on the modeling of Section III are a very good fit for the experimental results of pixel C on $LaAlO_3$ and $SrTiO_3$ substrates.

In this study, we did not investigate the effect of substrate thickness on the crosstalk between the pixels. However, based on previously reported single pixel studies [11], [12], as the

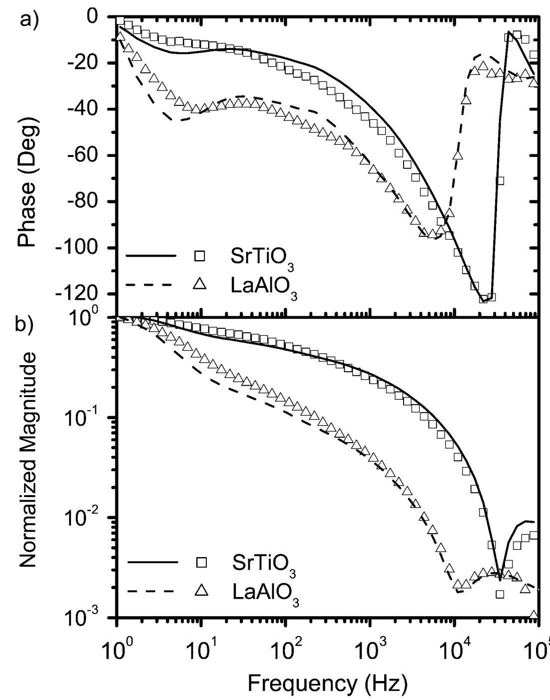

Fig. 4. (a) Phases and (b) magnitudes of pixels C on $LaAlO_3$ and $SrTiO_3$ substrates and their fitting curves.

thickness of the substrate decreases, the thermal diffusion length becomes comparable to the thickness of the substrate at higher frequencies as shown in (2), and the Kapitza boundary resistance affects the response for a higher ranges of frequencies. For example, in Fig. 4(a), the knee point around 4 Hz, caused by Kapitza boundary resistance, is clearly seen in the phase vs. frequency plot of $SrTiO_3$. Based on (2), as the thickness is decreased, the knee point is expected to shift to higher frequency values, decreasing the crosstalk at a higher rate.

Apart from the thermal parameters of the substrates material, it is observed that the crystal structure of the substrate also affects the response of the bolometers. The bolometers made on $SrTiO_3$ did not show much dependence on back-etching; however, back-etching the $LaAlO_3$ substrate-based bolometers considerably affected the response at an unexpectedly low modulation-frequency range.

C. Effect of the Substrate Back-Etching

Basically, back-etching removes the interface between the substrate and the cold-head. Thus, there should be no effect of Kapitza boundary resistance. For example, the thermal diffusion length of $SrTiO_3$ based bolometers, shown in Fig. 5, is 1 mm at 4 Hz modulation frequency. At frequencies below 4 Hz, the heat wave is expected to face the boundary resistance that reduces the phase of the response [11], [12]. However, since there is no such boundary in the back-etched bolometers, the phase of the response ends up being higher compared to the normal substrate based bolometers.

At frequencies where the propagating heat is not expected to face the boundary, the response is expected to be independent of the back-etching [5], [6]. As Fig. 5 shows, the response of the bolometers on $SrTiO_3$ substrate was as expected. However,

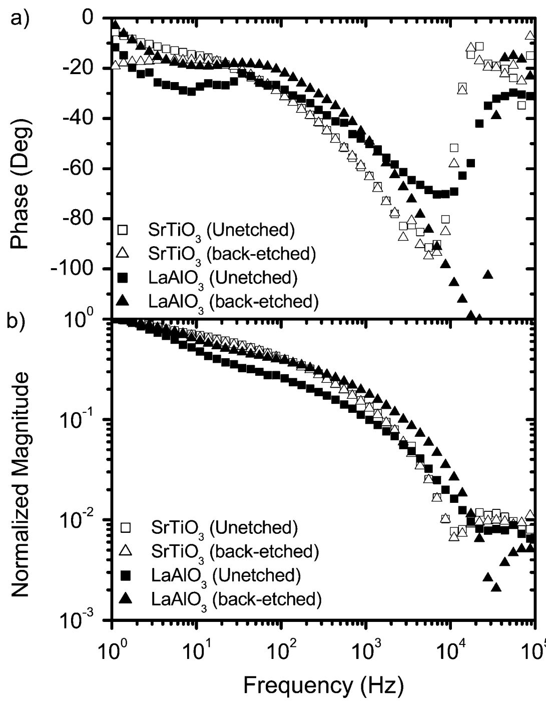

Fig. 5. (a) Phases and (b) magnitudes of back-etched and unetched bolometers made on $LaAlO_3$ and $SrTiO_3$ substrates.

the bolometers made on $LaAlO_3$ showed a clear dependence on back-etching even at higher frequencies where the thermal diffusion length is supposedly much shorter than the substrate thickness. This result is different from that predicted by the classical models and needs further detailed investigation [5], [6], [9]. To verify that this was due to the substrate-specific result, we repeated the experiment with different $LaAlO_3$ and $SrTiO_3$ based bolometers; these led to similar results. Since the thermal conductance and the thermal capacitances of both substrates are close to each other, [13] we attribute this discrepancy to the twinned structure of the $LaAlO_3$ material possibly affecting the phonon propagation mechanism; the physical reasoning behind this is under investigation.

V. Summary and Conclusion

In this study, we investigated the dependence of the crosstalk between the pixels of bolometer arrays with various device parameters. Some device parameters cannot be freely chosen because of practical constraints, but there are still enough controllable parameters to obtain the desired response characteristics. In addition we have demonstrated an analytical model for explaining the thermal crosstalk-based response behaviors of bolometer arrays. We also showed that film thickness is one of the main parameters affecting the crosstalk and as film thickness increases, the crosstalk increases. We further showed that the response of $LaAlO_3$ substrate-based bolometers depends unexpectedly strongly on back-etching even at high frequencies where the thermal diffusion length is expected to be smaller than the substrate thickness. We concluded that $LaAlO_3$ is not a suitable substrate material for bolometer arrays due to the observed unfavorable anomalies, the reason of which is out of scope of this paper.

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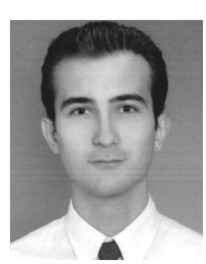

Ali Bozbey (S'98) was born in September 27, 1979 in Isparta, Turkey. He received the B.S. and M.S. degrees in electrical and electronics engineering from Bilkent University, Ankara, Turkey, in 2001 and 2003, respectively, where he is currently working toward the Ph.D. degree.

He has been a teaching and research assistant at Bilkent University since 2001. He has developed an automated high-temperature superconducting bolometer characterization setup. He is currently working on the high-frequency response characteristics of bolometers and the crosstalk in the bolometer arrays. His research interests include the design and modeling of high-temperature superconducting infrared detectors in combination with SQUID based read-out electronics. He is the author and coauthor of several journal publications and has been the vice chair of Bilkent IEEE Student Branch at Bilkent. He has worked as one of the coordinators for the establishment of 10 new IEEE student branches in Turkey.

Mehdi Fardmanesh (M'90–SM'01) was born in Tehran, Iran, in 1961 and received the B.S. degree from Tehran Polytechnic University, Tehran, and the M.S. and Ph.D. degrees from Drexel University, Philadelphia, PA, all in electrical engineering, in 1987, 1991, and 1993, respectively.

In 1989, he joined the graduate program at Drexel University, where he was awarded a research fellowship by the Ben Franklin Superconductivity Center in 1989, and till 1993, he conducted research in development of thin and thick film high-temperature superconducting materials and devices, as well as development of ultra-low noise cryogenic characterization systems. From 1994 to 1996, he was principal manager for R&D and the Director of a private-sector research electrophysics laboratory, while also teaching at departments of Electrical Engineering and Physics of Sharif University of Technology, Tehran. In 1996, he joined the Electrical & Electronics Engineering department of Bilkent University, where he teaches in the areas of solid-state, and electronics, while supervising the superconductivity research laboratory. In 1998 and 1999, he was invited to ISI-Forschungszentrum, Juelich, Germany, where he pursued the development of low-noise High-T_c rf-SQUID-based magnetic sensors. From 2000 to 2004, he was the international director of the Juelich-Bilkent joint project for "development of High Resolution High-T_c SQUID based magnetic imaging system." Since 2000, he has also been with the Electrical Engineering Department of Sharif University. His research interests are focused in the areas of high-temperature superconductive bolometers, Josephson Junctions, and SQUID based systems.

Dr. Fardmanesh received the Outstanding Graduate Student and Best TA awards from Drexel University.

Juergen Schubert was born in Cologne, Germany, in 1958. He studied physics in Cologne and received the Diploma degree in physics in 1985. He received the Ph.D. degree from the University Köln, Cologne, in 1989.

He joined Research Center Juelich, Germany, in 1984. From 1985 to 1989, he developed a high-pressure sputter technique for the growth of high-temperature superconductor thin films. Since then, he is the leader of the laserlab of the ISG 1-IT of the Research Center Jlich and he is responsible for the growth of epitaxial oxide thin films (superconducting, ferroelectric, optical transparent, conducting etc.) using the pulsed laser deposition method. In 2002, he spent 1 year at the Pennsylvania State University, State College, as a Guest Scientist in the Oxide Molecular Beam Epitaxy Group of D. Schlom.

Marko Banzet was born in Dinslaken, Germany, in 1973.

He joined Research Center, Juelich, Germany, in 1989 as an Physics Laboratory Assistant. Since 1992, he is a Technician in the field of superconductivity, thin film deposition, ion beam etching, lithographic structuring, and clean room technology. Currently, he participates in vocational training as Information Technology Engineer.