Fabrication of Infrared Antennas using Electron Beam Lithography

Michael A Gritz*, Javier González, and Glenn D. Boreman*a
School of Optics/CREOL

Abstract

The methods of fabricating infrared antennas using electron beam lithography will be investigated. For this purpose, a process using a bi-layer lift off process and a single layer of resist has been developed. The bi-layer lift off process used allowed for antenna arm resolution of 200nm. The single layer resist process enhanced the resolution of the antenna arms to 90nm by using a Chlorine based reactive ion etcher with Chrome as an etch mask. An alignment scheme using a set of global and local marks allowed for an overlay accuracy of 25nm. An improved process was developed to further improve device yield and uniformity of the infrared detectors by sputtering the bolometer and using an oxygen descum to remove residual resist between the antenna and bolometer. Two separate methods of fabrication of air-bridge microstrip antenna-coupled microbolometers using both a critical point dryer and an isotropic reactive ion etcher will also be introduced.

Keywords: Infrared antenna; Microbolometer; Infrared detector

1. Introduction

Conventional microbolometers have been used as thermal detectors for infrared (IR) radiation by making use of the change of the bolometer resistance with an increase in the temperature either by absorbing the irradiation directly or absorbing the heat power by a radiation absorber[1]. In the case of an antenna-coupled microbolometer, the incident field is received by the antenna. Then the induced current on the antenna passes through the microbolometer, which causes a change in resistance in the bolometer by Joule heating. An SEM micrograph of a dipole antenna-coupled microbolometer is shown in Fig. 1. The advantage of antenna-coupled microbolometers is their room temperature operation, their tunability for wavelength and polarization response. Antenna-coupled microbolometers and metal-oxide-metal detectors have been demonstrated in the infrared at wavelengths near 10μm[2-4]. Work has been done in fabricating a thin-film niobium antenna-coupled microbolometer element[5-6].

In this paper we present our work on the fabrication of a thin-film infrared antenna-coupled microbolmeters using electron beam (e-beam) lithography. We will discuss the alignment techniques used in the fabrication of lithographic antenna-coupled microbolometers. Also two different processes used in e-beam lithography will be developed. The first process discussed will be a bi-layer lift off process. The next process uses a single layer of polymethyl methacrylate (PMMA) in conjunction with a reactive ion etcher (RIE) to enhance the resolution of the dipole antenna arms. The effects of the substrate on the device performance will also be discussed. We will also examine the contact issues between the antenna and the detector. Furthermore, fabrication of microstrip antenna-coupled microbolometers will be discussed, which includes the techniques developed in creation of air bridge microstrip antenna-coupled microbolometers.

* mgritz@creol.ucf.edu; phone 1 407 823 6843; fax 407 823 6880; http:// ir.creol.ucf.edu; School of Optics/CREOL, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL, USA 32816
*a boreman @ creol.ucf.edu; phone 1 407 823 6815; fax 407 823 6880; http://ir.creol.ucf.edu; School of Optics /CREOL

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2. Fabrication Techniques

The antenna-coupled microbolometers were fabricated at the Cornell Nanofabrication Facility using a Cambridge/Leica EBMF 10.5 direct write e-beam lithography system. The advantage in using e-beam lithography is the high resolution. The disadvantage is the throughput when compared to optical lithography. Another limitation with an e-beam lithography tool is in the interaction that takes place between an electron

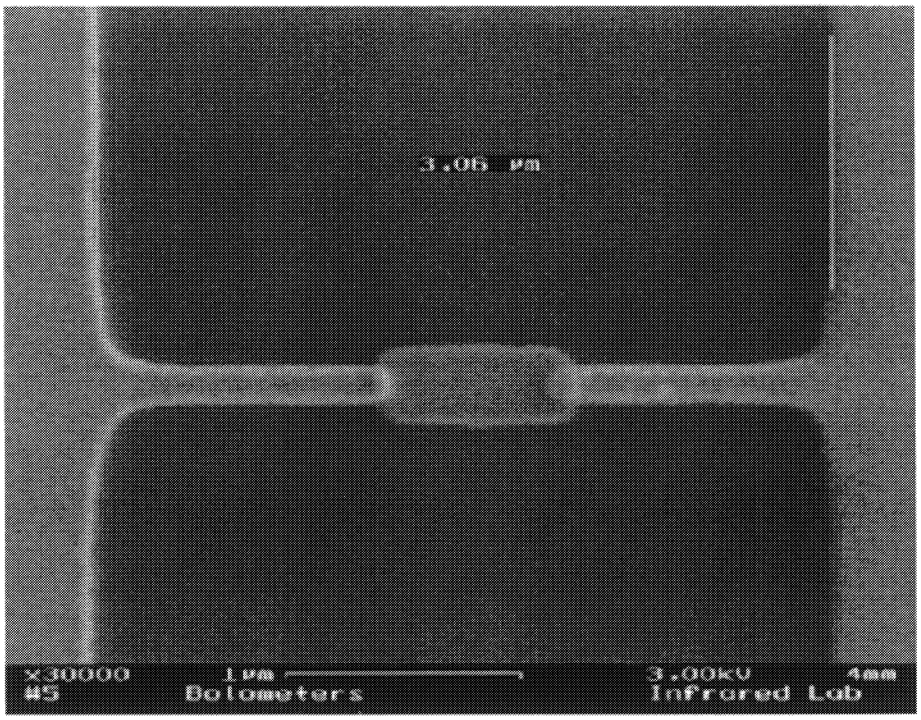

Figure 1. SEM micrograph of an antenna-coupled microbolometer.

and the sample. As the primary electrons move through the resist much of their energy is dissipated, which forms secondary electrons with energies ranging from 2 to 50 eV. The secondary electrons are responsible for the actual resist exposure. This effectively contributes to the widening of the beam diameter. The width depends on the molecular weight of the resist used. For PMMA this width is approximately 10nm. The electrons also experience small angle scattering events known as forward scattering. Forward scattering results in a broader beam profile at the bottom of the resist than at the top of the resist, which can be minimized by using the thinnest possible resist and the highest available accelerating voltage. This addition from the secondary electrons along with the forward scattering contributes to the bias that is commonly seen in positive resist systems. Bias is where the exposed features develop larger than the size they were normally written. After the electrons penetrate the resist and begin to penetrate the substrate, the electrons undergo large angle scattering events referred to as back scattering. These electrons may return back through the resist causing accidental resist exposure, which is called the proximity effect.

The primary goals for an e-beam resist are the highest resolution, high throughput (high sensitivity), and high etch resistance. However, the highest resolution resists are usually the least sensitive. In a basic positive resist, the electron energy breaks the polymer backbone bonds. This scissioning of the bonds leaves fragments of lower molecular weight. In a basic negative resist, the electron energy essentially causes crosslinking the polymer chains together, which means increasing the molecular weight. Therefore rendering the resist less soluble in the developer. Negative resists tend to have problems with swelling, which results in snake like distortions from the crosslinking.

A basic process is to spin on resist, which is usually a polymer dissolved in a liquid solvent. The resist can be spun onto the substrate from speeds ranging from 1000 to 6000 rpm. The substrate is then baked to remove any solvents. The substrate is exposed to a variety of doses. The resist is modified from the exposure making it either more soluble (positive acting) or less soluble (negative acting) to the developer. The patterns can then be transferred to the substrate by an etching process or a liftoff. In a liftoff process, a material is evaporated from a source onto the substrate and resist. The substrate is then immersed into a solvent, which removes the resist.

PMMA is the classical e-beam resist. PMMA offers the advantage of extremely high resolution and ease of handling. The major disadvantage of PMMA is it is insensitive and does not have an efficient etch resistance. PMMA is commonly used in two molecular weights either 496k or 950k with a solvent of either anisole or chlorobenzene. When PMMA is exposed to 10 times the optimal positive dose, PMMA will crosslink, forming a negative resist. Attempts to improve the sensitivity of PMMA led to new resists with higher sensitivities. One such resist is a copolymer of PMMA, the resist is prepared by copolymerizing methyl methacrylate and methacrylic acid P(MMA-MAA).

2.1 Alignment techniques

The first set of detectors we fabricated were Aluminum dipole antennas with Niobium as the detector, which is shown in Fig. 2. In order to fabricate antenna-coupled microbolometers, precise alignment of the antenna to the detector is required. This is accomplished by using a set of alignment marks. When both local and global alignment marks are used the best overlay accuracy is obtained. The global marks were used to correct for any rotation errors while loading the substrates into the chuck, whilst the local marks were

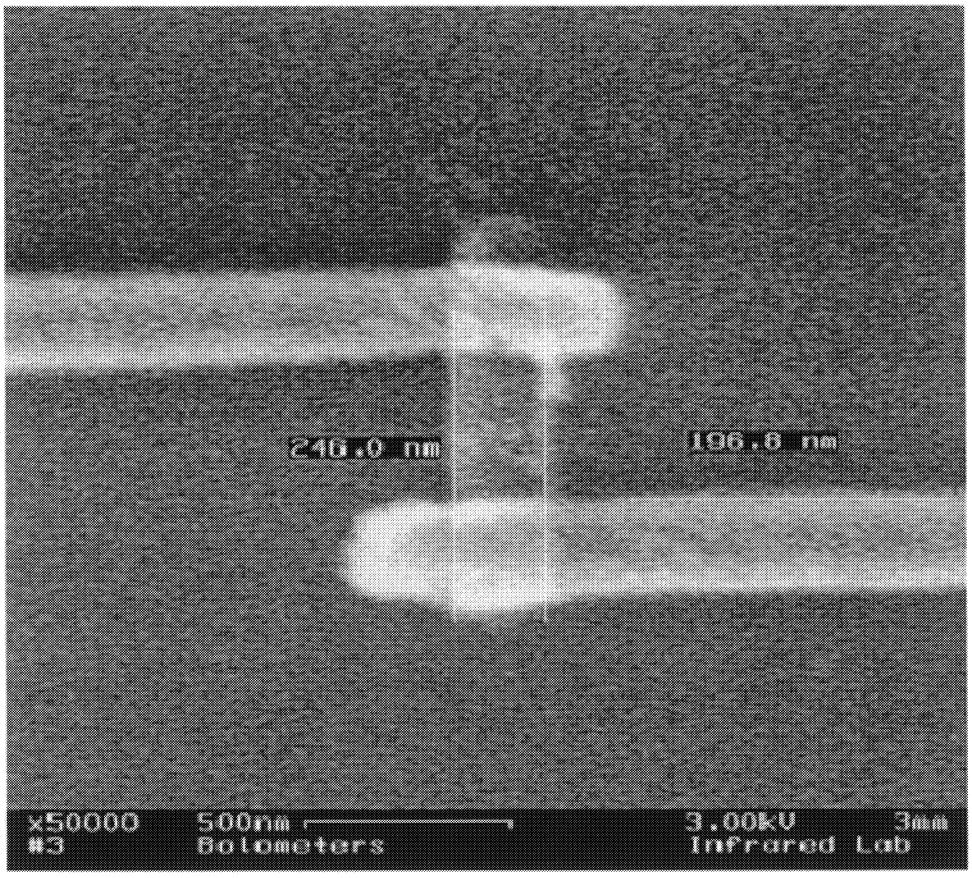

Figure 2. First set of antenna-coupled microbolometers fabricated using Aluminum for the dipole antenna arms.

used to correct for any stage drift when moving from field to field. A similar alignment scheme was employed in[7], which had an overlay accuracy of less than 25 nm. Another alignment scheme used high contrast alignment marks, which were fabricated by reactive ion etching into Si[8]. The etched holes in the Si should be less than 1μm in order to prevent resist pooling during device processing. The EBMF uses a backscatter detector to detect secondary electrons to accomplish precise alignment, which means that an element with a high Z number is more effective. The EBMF used the contrast between the marks and Si substrate to detect the marks.

2.2 Bi-layer liftoff process

The liftoff technique is a common processing technique used among e-beam lithographers. In a liftoff process the thickness of the metal will determine the type of resist profile employed. For thinner material (< 50nm), a single layer of PMMA or a bi-layer consisting of two different molecular weights of PMMA may be used [see Fig 3a]. For applications that require a thickness greater than 50nm, a bi-layer liftoff process is used. A bi-layer liftoff process uses two layers of resist. The bottom layer is P(MMA-MAA). The P(MMA-MAA) layer has a larger undercut because of its higher sensitivity. The second layer is PMMA [see Fig. 3b]. PMMA will be the ultimate resolution of the entire system, when e-beam evaporaion is used because e-beam evaporation is considered to be a point source, which implies that the material will fall onto the resist and substrate [see Fig. 3c]. This will provide a clean separation of the material allowing for a solvent, which dissolves the resist, to undercut the resist [see Fig. 3d].

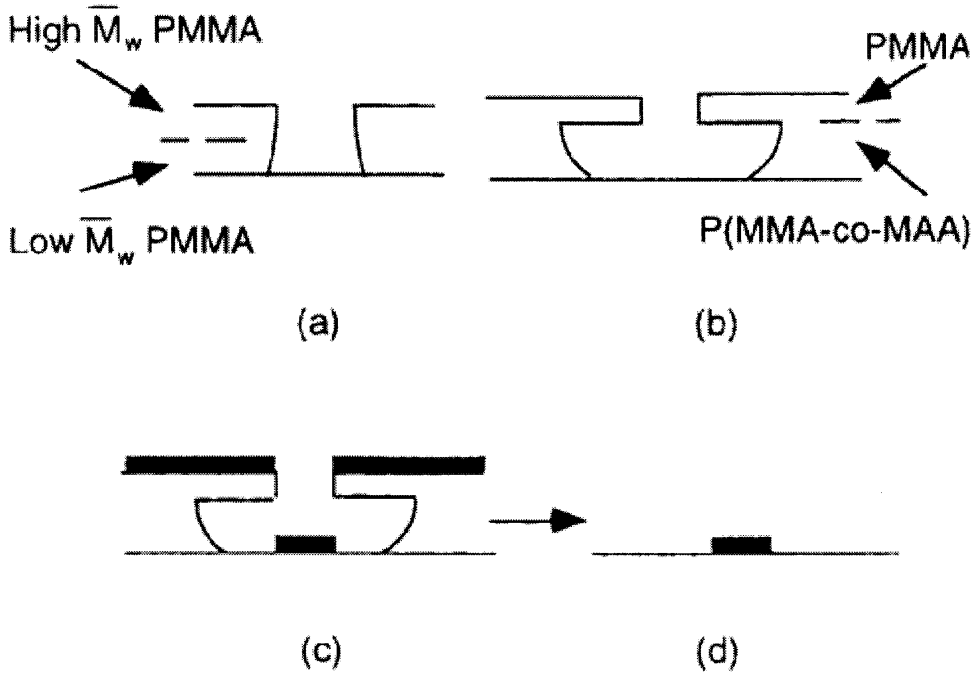

Figure 3. The basic process for a bi-layer liftoff either using a combination of a low/high molecular weight PMMA or using PMMA/P(MMA-MAA)[9].

2.3 Single layer resist process

We have also demonstrated a new process, which uses a RIE with Chromium as an etch mask for the fabrication of the Aluminum dipole antennas, rather than using a traditional lift off process for the Aluminum dipole antenna arms. First the wafer is coated with 100nm of Aluminum [see Fig. 4a]. Next a

single layer of PMMA is spun on to the wafer to lift off 40nm of Chromium [see Fig. 4b]. Then the Aluminum is removed with an RIE using 1.5 sccm Cl_2, 40 sccm BCl_3, and 20 sccm CH_4 for 1 minute [see Fig. 4c]. The final step is to remove the Chromium [see Fig. 4d] by using a resist strip in a Branson barrel etcher with a pressure of 1 Torr for 3 minutes at 1000 Watts because it was found that Chrome etchant also removed Aluminum[9]. The process allowed for a single layer of resist to be used, which enhances our line width control. Our process yielded line widths of 90nm for the antenna arms. The results of this process are shown in Fig. 5.

2.4 Improved fabrication process

Both the bi-layer and single layer resist processes yielded marginal results. There were severe problems with the uniformity from chip to chip and with non-linear contacts between the antenna and the detector, which were thought to be caused by a contamination of the resist. Therefore, an improved fabrication process was developed. In the new process, the bond pads and antenna arms were all fabricated with Gold as one layer because of concerns about contact related issues. Gold was used because it does not oxidize, which may lead to bad contacts between the antenna arms and the bolometer. Another modification made to the process came during the development procedure. The first change was a fresh batch of MIBK:IPA should be mixed because old developer was found to cause unwanted fluctuations from wafer to wafer. After the development of the substrates, the next step in the improved process was to remove any unwanted resist, which may have been left behind after the development but not seen under an optical microscope. The presence of such a thin layer of resist was found to lead to bad contacts between elements

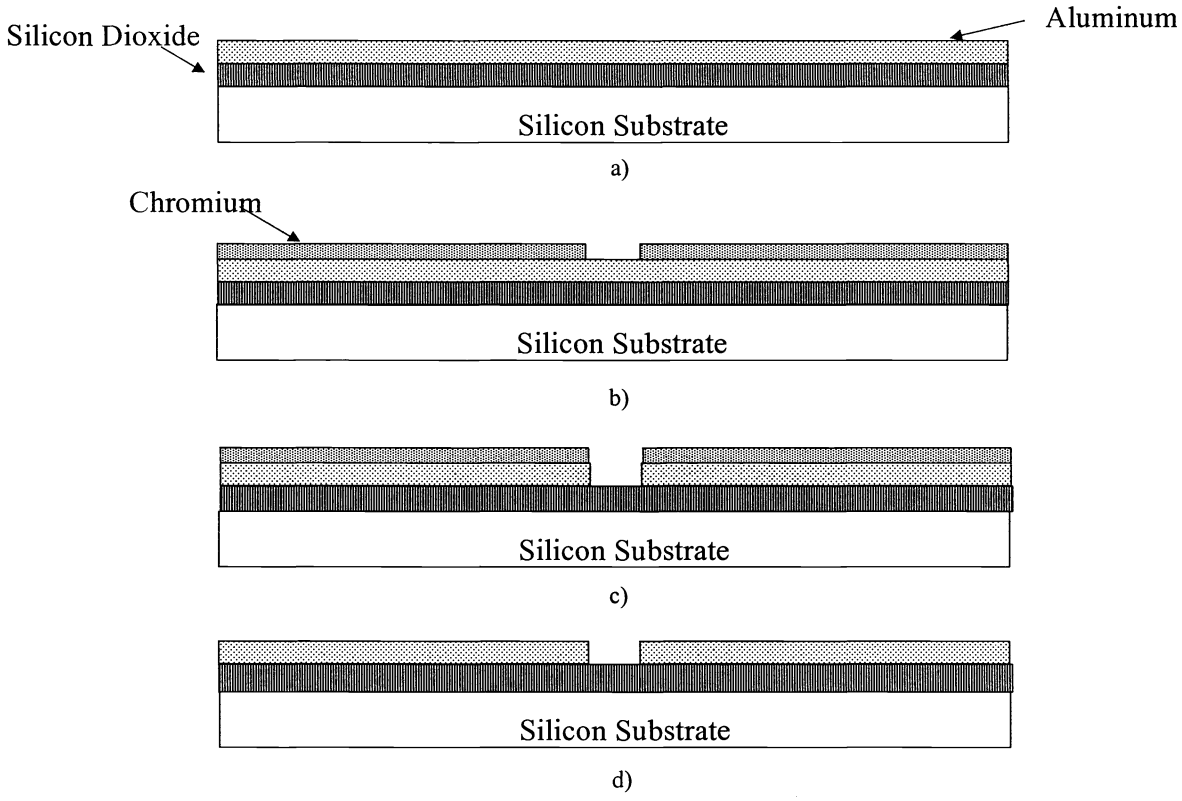

Figure 4. Details of the process used to fabricate the devices using a single layer of PMMA using an RIE with Chromium as an etch mask[10].

in our bolometers. The thin layer of resist was removed by oxygen plasma in a Branson barrel etcher. This was done each time immediately after the development of the substrates[10]. The next change was in the deposition method for the Niobium detector. For the new process, the Niobium was sputtered on to the substrates because e-beam evaporation of Niobium requires higher beam current. The higher beam current leads to a higher substrate temperature, which causes re-flow of the resist leading to a non-linear contact between the bolometer and the antenna. Fig. 1 shows an SEM micrograph of the improved device.

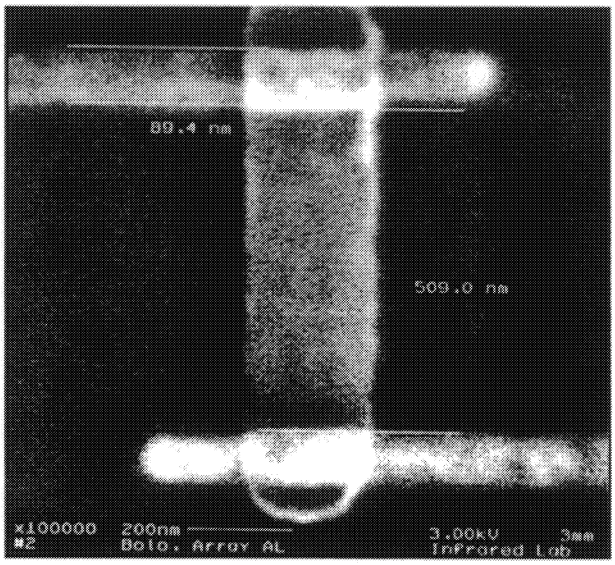

Figure 5. Results of new process developed using an RIE to remove the Aluminum.

2.5 Microstrip antenna-coupled microbolometers

Now with a method of consistently fabricating antenna-coupled microbolometers, the next advancement was to fabricate microstrip antenna-coupled microbolometers, which is simply a microbolometer on top of a dielectric coated ground plane. The addition of a Gold ground plane coated with SiO_2 lead to a 3× increase in the response of the device[11]. There was also a shift in resonance of the antenna to lower wavelengths. To further increase the responsivity of the detector, the SiO_2 was replaced by Air, which thermally isolated the antenna from the Si substrate. There were two different processes developed to fabricate air-bridge antenna-coupled microbolometers. The first process developed used Aluminum or SiO_2 as the sacrificial layers. A critical point dryer using liquid CO_2 was used to replace the etchant used to remove the sacrificial layer. The liquid CO_2 is brought passed its critical point, where it will flash to a gas causing the bridge to be released with out any undo surface tension. The results of the critical point dryer process are shown in Fig. 6. With air replacing the SiO_2 coated Gold ground plane lead to a 50× increase in the response of the device[11].

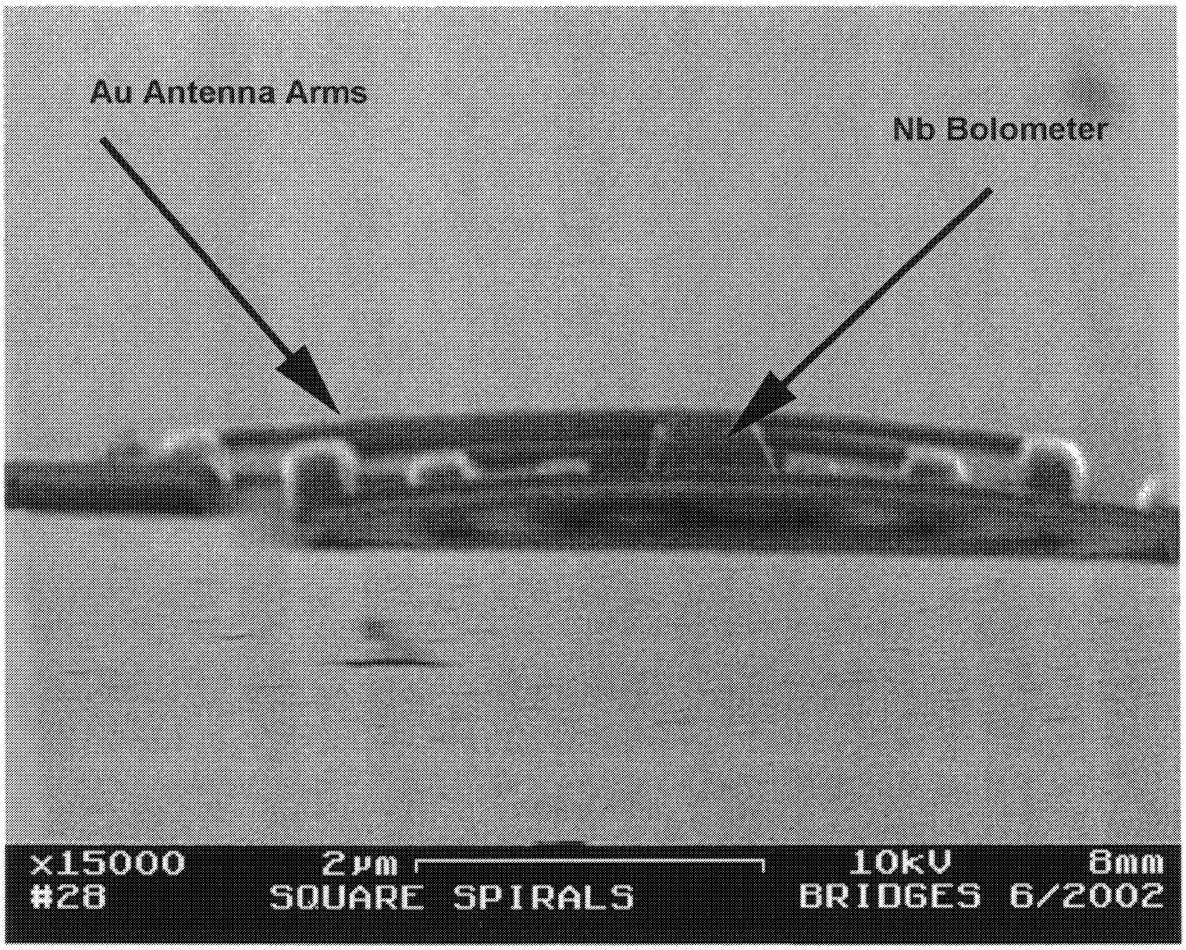

Figure 6. An SEM micrograph showing the results of an air-bridge spiral antenna-coupled microbolometer after using a critical point dryer.

The second process developed used an isotropic RIE to remove the sacrificial layer of PMMA. First a bi-layer liftoff process is used to deposit 100nm of Gold onto the wafer to form a coplanar waveguide transmission (CPW) line [see Fig. 7a]. Next a single layer of PMMA is spun on to the wafer to form the sacrificial layer [see Fig. 7b]. This is accomplished by first exposing the area where the Au bridge is desired, which will pattern the base of the bridge. Then the PMMA is overexposed, which causes the resist to cross-link, in the area where the PMMA will act as the sacrificial layer. After the development, an oxygen plasma etch was performed for 1 minute. Then a 50nm layer of Chromium was thermally evaporated onto the substrate to help protect the PMMA from being washed away by the acetone during the lift off process of the

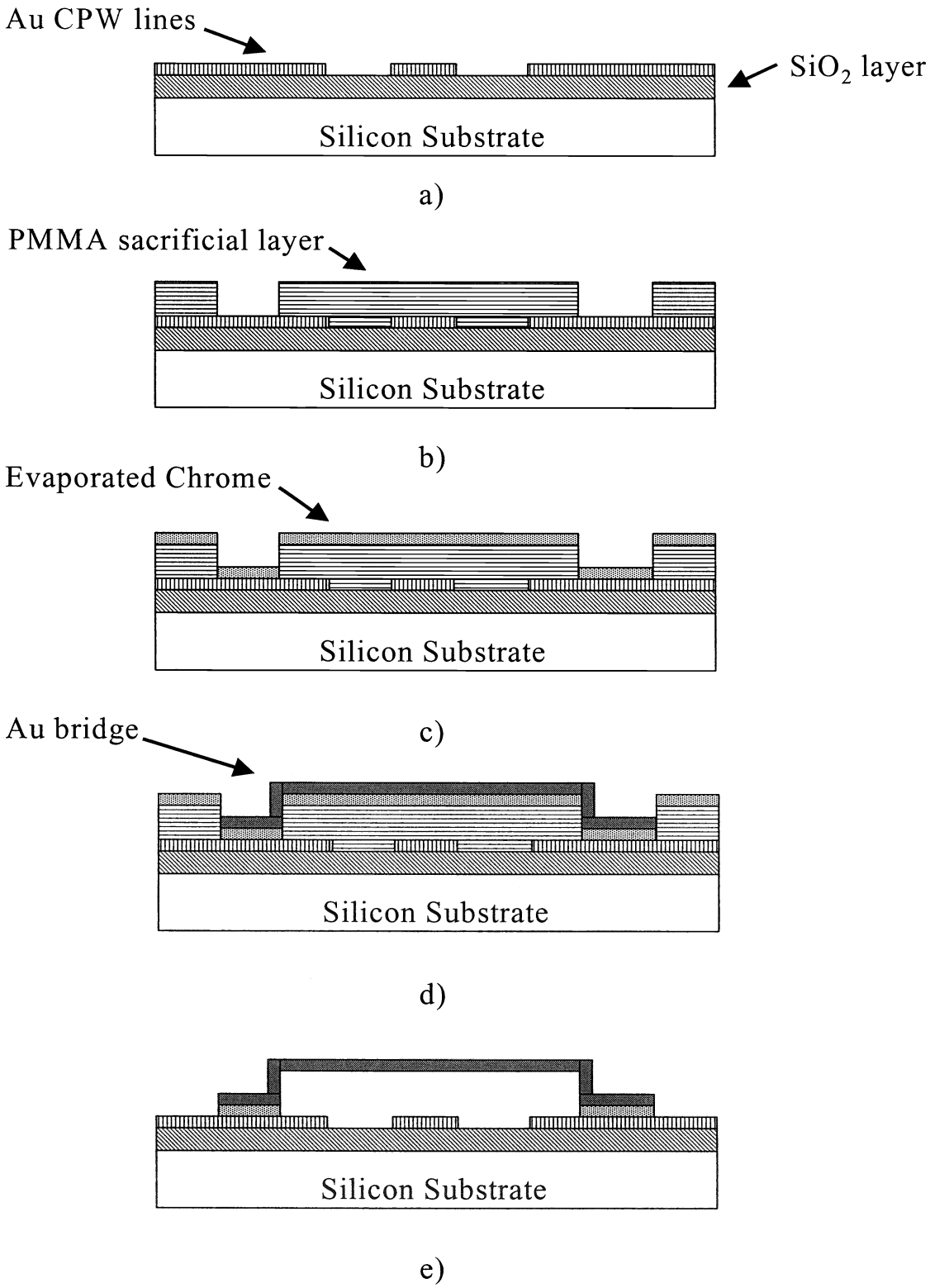

Figure 7. Details of the fabrication process for the air bridges made using an isotropic RIE[7].

Gold bridge [see Fig. 7c]. The final step in the fabrication of the air bridges is to create the Au bridge on top of the PMMA sacrificial layer using a liftoff process [see Fig. 7d]. The substrates were baked on a hotplate set to 115°C for 30 minutes. The temperature was lowered to 115°C because both PMMA and PMMA-MAA will re-flow at approximately 120°C. After development and an oxygen plasma etch was performed for 1 minute, 10nm of Chromium and 250nm of Au was e-beam evaporated on to the substrates. The unwanted resist and metallic films were lifted off using acetone. Next the substrates were placed in a Chrome etchant for 20 seconds to remove the Chromium layer. Once the Chromium was removed, a resist strip was done using oxygen plasma on a Branson barrel etcher [see Fig 7e]. A barrel etcher is an isotropic etch, which means it etches equally in all directions. So the etch time was set to 4 minutes in order to ensure that all the PMMA under the Au bridge was etched away. After the etching of the PMMA, the air bridges were examined using a scanning electron microscope (SEM). Micrographs taken from the SEM can be seen in Fig. 8 clearly indicate an air bridge[7]. The major disadvantage to this process when compared to a critical point dryer is the amount of thermal stresses generated by the oxygen plasma, which causes the bridges to bend upwards.

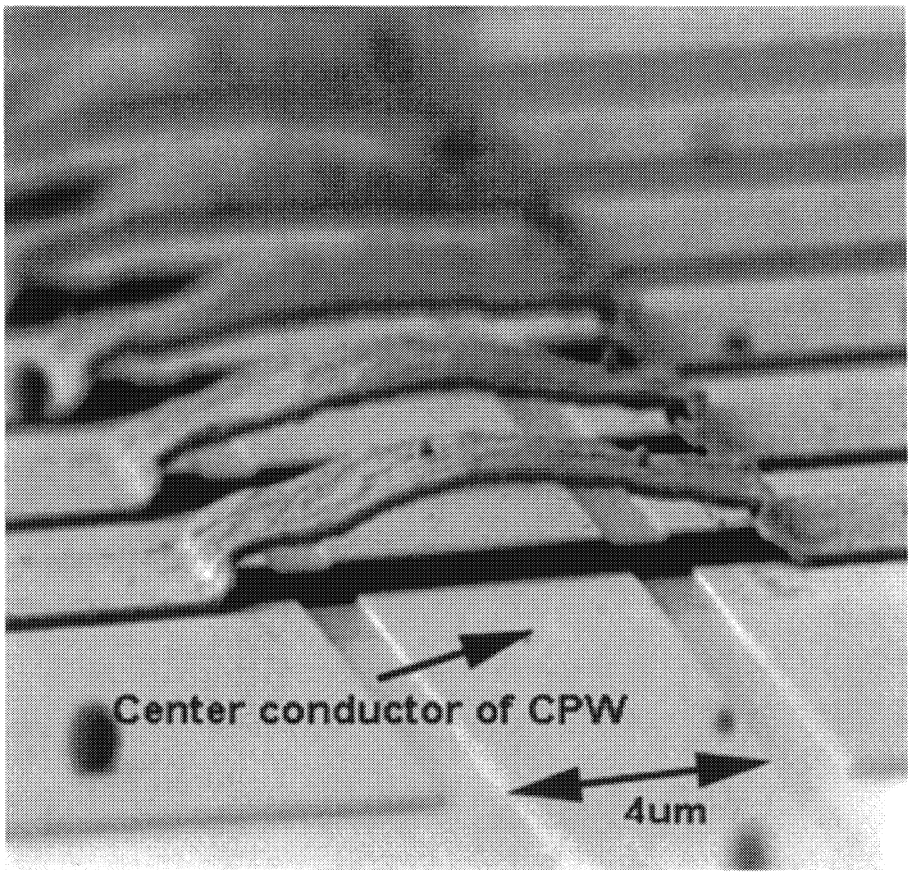

Figure 8. A SEM micrograph of an air bridge showing the results of the isotropic RIE process.

3. Results

The substrate used to fabricate the detectors was a 380μm-thick high-resistivity Si wafer (ρ = 3kΩ cm). Both sides of the wafer were polished, which allowed for illumination from either side of the substrate, and coated with 200nm of thermally grown SiO_2. The SiO_2 layer was used for an electrical and thermal

isolation. The spectral properties of the Si substrate was measured with an fourier-transform infrared (FTIR) spectrometer and yielded a power transmission through both surfaces of 52% at 10.6μm. We fabricated 30 different antenna with lengths varying from 0.7 to 20.0 μm. The chips of detectors were mounted on a chip carrier, which allowed for illumination from the front side (air) and backside (Si) of the wafer and bonded using an ultrasonic bonder[12]. By illuminating through the substrate, the responsivity of the device increases by a factor of 2.3[6]. The inherent problem with substrate-side illumination is the difficulty in integrating the detector with existing readout and multiplexer electronics.

4. Conclusions

We have demonstrated several fabrication techniques used in e-beam lithography for the fabrication of antenna-coupled microbolometers. An alignment scheme using a backscatter detector with a set of global and local marks was developed to allow for an overlay accuracy of 25nm. Two separate fabrication processes common to e-beam lithography have been developed. The first process consists of a bi-layer liftoff process. The second process used a single layer of PMMA inconjuction with a RIE to enhance the ultimate resolution of the process. Furthermore, several improvements were made on the process to increase the yield and uniformity by using an oxygen descum process and sputtering the detector rather than using e-beam evaporation.

Two methods for fabrication of an air bridge antenna-coupled microbolometer have been developed in this work. The first method used SiO_2 as the sacrificial layer. The process uses a critical point dryer, which uses liquid CO_2 to replace the etchant used to remove the SiO_2. This process yielded a device with increased responsivity when compared to a microstrip antenna-coupled microcbolometer with SiO_2 as the dielectric spacer. The second process used a Branson barrel etcher to remove the PMMA sacrificial layer. Because this process uses PMMA it could be further developed to lead to a whole new area of processing for nano-air bridge structures.

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