Micromachined LCP Connectors for Packaging MEMS Devices in Biological Environments

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Abstract

Micro- and nano-MEMS technology is being increasingly exploited in biological applications, such as large electrode-count neural prosthesis probe arrays. However, a bottleneck in fully utilizing this technology has been the interconnect between the implanted MEMS device and the external system connected to the implanted device. Since the implanted MEMS device is capable of having a large number of elements, the interconnect must have a sufficient number of electrical connections to communicate with each and every element. Complicating this is the fact that the interconnect requirements may include electrical signals, microfluidics transport and optical signals, all packaged in a miniature biocompatible interconnect cable. Micromachined liquid crystal polymer (LCP) is a promising technology for this application, due to LCP's biocompatibility, chemical inertness, electromechanical properties and its ability to be micromachined. This paper presents the results from the development of MEMS packaging technology suitable for use in biological environments, and is demonstrated in the realization of a prototype micromachined LCP biomedical interconnect device. In particular, the development of the interconnect device demonstrates the realization of biocompatible connectors with high-density ultra-fine pitch electrical traces.

Keywords

Packaging, MEMS, Micromachined, Biomedical, LCP

Introduction

Numerous researchers are developing MEMS based electrodes for recording and/or stimulating neurons in the central nervous system [1]-[7]. The use of high-precision photolithographic and thin-film techniques employed in the microelectronics industry results in devices with a wide design space, highly reproducible electrical and geometrical characteristics, and very small features, all of which are highly desirable characteristics for a neuroscience research tool. The University of Michigan has developed a silicon-based probe, the so-called “Michigan Probe,” which they have made available to investigators across the world through the Center for Neural Communication Technology for use in a broad range of neuroscience disciplines [8]-[11]. A photograph of an example device is presented in Figure 1. This particular device is a four-shank Michigan Probe. The gold squares on the left are bond pads for connection to the external world. Four iridium recording sites can be seen at the tips of each of the four shanks. Each shank on this probe design is 4 mm long. The probe would be attached to an interconnect cable for electrical connection to the outside world. Electrical connection to the cable can be accomplished by several methods, including gold wirebonding, conductive adhesive and soldering. Typically though, each of these electrical connection methods requires a biocompatible protective coating, such as silicones, to protect the interconnection from the biological environment and to protect the organism from biologically incompatible electrical interconnection materials.

Chronic recordings have been successfully obtained from these probes in guinea pigs and rats using a monolithic silicon ribbon cable as the interconnect to the external world [12]-[13]. Silicon cables are extremely flexible, but only in one dimension. In addition, lengths longer than several centimeters are not practical due to high aspect ratios, which lower yields. Therefore, as these devices are used in higher species and more mechanically treacherous environments,

such as the spinal cord, a longer more robust interconnect will be required to withstand increased surgical manipulation and larger relative movements. Flexible printed circuit board technology is a potential candidate for use as the ribbon cable interconnect, and liquid crystal polymer (LCP) may be the best flexible printed circuit board material for this application. LCP is biocompatible and can be micromachined to realize interconnect devices for mechanical, electrical, microfluidic and optical interconnection.

Figure 1. A photograph of a four-shank Michigan probe.

Liquid Crystal Polymer

LCP is a thermoplastic material consisting of aligned copolymer molecules [14]. Each LCP molecule is constructed of rigid and flexible monomeric units. The rigid monomer gives the molecule its high temperature capability and mechanical properties, while the flexible monomer allows the molecule chain to be processed. When LCP is in the liquid state and can therefore flow, the nature of this type of polymer molecule is to self align with other LCP molecules in the shear flow, much like logs flowing in a river. This results in the creation of locally oriented domains, which create macroscopically oriented regions in the material. After the formation of oriented regions in the liquid state, the long relaxation time of the molecules keeps them aligned during and after solidification. This results in a uniaxially-oriented film, with good material properties along the direction of orientation, but poor properties along the transverse, in plane direction. This type of film would be of little use. However, a manufacturing process developed by Foster-Miller, Inc., that utilizes counter rotating die during extrusion, can be used to create a biaxially-oriented film, with some of the molecules aligned along the direction of extrusion and the rest aligned along the in-plane transverse direction orthogonal to the direction of extrusion. In a uniaxially-oriented film, the molecules are all aligned along the direction of extrusion. In a biaxially-oriented film, the molecules are aligned in the two in-plane directions, $\pm\phi$ degrees with respect to direction of extrusion. For isotropic in-plane properties, this orientation angle is 45^{o}.

Biaxially-oriented LCP is currently being used as a high performance printed circuit board material, due to its higher working temperature than FR-4 style laminates, its good high frequency properties and its chemical resistance and barrier properties. Although thick sheets of laminated LCP are useful as rigid printed circuit boards, thin sheets (25 to 50 μm) are suitable for use as flexible printed circuit boards. Of particular interest to applications in biological environments, is the fact that LCP is a biocompatible material. LCP can also be micromachined to realize precision electromechanical features, which can be useful for these applications

Previously Published Work

LCP has been investigated as a suitable material for MEMS applications in recent years, with a number of microfabrication techniques having been successfully applied to micromachining LCP, including photolithography, lamination, wet etching, dry etching and embossing [15]-[20]. Since biaxially oriented LCP is being utilized as a high temperature printed circuit board material, it is readily available in sheets of 12 inches by 18 inches, and in thicknesses ranging from 25.4 μm to multiples of 25.4 μm, both with and without copper cladding. Therefore photolithography can be accomplished using either dryfilm techniques borrowed from the printed circuit board industry, or liquid photoresist techniques on smaller samples using silicon microfabrication techniques. Typically, when using liquid photoresist techniques, the LCP substrate is first attached to a rigid holder, such as a silicon wafer, through a variety of temporary bonding techniques (adhesives, photoresist, lamination, etc…). Wet etching of LCP is typically performed using heated alkaline solutions, such as 46% concentration KOH at 90^{o}C. Patterned copper cladding is currently the material of choice for masking the LCP substrate during wet etching. Dry etching is usually performed using oxygen based plasma chemistries in either RF reactive ion etchers (RIE) or in non-RIE downstream plasma etchers. For dry etch masking, either patterned copper cladding or patterned thin film aluminum is used. LCP can be laminated to a variety of materials, including LCP, silicon, glass, and metals. Presses and autoclaves are used to perform the lamination process. A variety of features can be embossed into LCP substrates using molds made by conventional precision machining or by micromachining of silicon. Lasers can be used to spot weld or etch LCP. Laser processing has the disadvantage of sequential processing but the advantage of localized heating.

Thin Film Processing on LCP

To date, most published work on micromachining of LCP has consisted of bulk micromachining of the LCP substrate. Relatively little research has been published on surface micromachining using LCP. Since most micro-machined LCP devices will, at some point, be integrated with electrical devices, it is vital to develop surface micromachining techniques for deposited thin films on LCP. These thin films may be electrically conductive

(sputtered or evaporated metal films) or nonconductive (sputtered or spin-on insulating materials). The LCP printed circuit board industry has demonstrated conductive traces on LCP as small as 2mils (50.8 μm) wide [21]. However, for many applications, including biological interconnects, it is desirable to realize much smaller conductor widths. LCP substrates have several characteristics that differ substantially from typical silicon substrates, including chemical composition and structure, rigidity, melting temperature, surface roughness and wetting properties. Therefore many, if not most, silicon based surface micromachining techniques are not directly applicable to LCP processing.

For this application, it is desirable to obtain biocompatible thin film electrical traces with widths in the 5 to 15 μm range on LCP. In order to accomplish this, a process had to be developed to insure satisfactory thin film adhesion to LCP. Since metallic thin film deposition on other plastic materials has been successfully performed for many years, it should be possible on LCP also. Thin film adhesion promotion on plastics typically consists of a surface treatment to promote wetting, followed by deposition of an adhesion layer and then the desired thin film layer.

Cold plasmas are often used as a surface treatment to modify the surface of polymers. Typical plasma processes include: ablation (microetching), surface cleaning, cross-linking and surface activation [22]-[23]. These four competing processes can be tailored by altering the plasma process conditions (gas content, power, etc…). Surface cleaning is typically a low power process (low energy bombarding ions) used to remove surface contaminants. Ablation requires higher energy ions that remove material from the surface by sputtering and/or the creation of volatile products through plasma activated chemical reactions. Plasmas created using diatomic oxygen gas contain a variety of oxygen species (positively and negatively charged monatomic and diatomic oxygen ions, oxygen atoms, ozone, ionized ozone and metastably excited oxygen molecules). The plasma environment, particularly due to UV photons, is particularly adept at breaking C-C and C-H bonds. The various oxygen species present in the plasma quickly scavenge the free radicals created by hydrogen abstraction and C-C bond breakage. The rate of oxidative degradation of the polymers is limited by the effectiveness of the C-C bond breaking in the plasma. Addition of fluorocarbons, such as CF4, to the oxygen based plasma greatly increases the etch rate due to the effectiveness of fluorine plasmas at breaking C-C bonds. Sputtering can be enhanced by adding high energy ions from inert gases, such as Ar, to the plasma mixtures, with a biased platen. Pure noble gas plasmas, such as Ar or He, can be effective at introducing cross-linking in many hydrocarbon materials. However, oxidation is generally the most effective plasma technique for increasing the surface energy, and therefore the wettability, of a plastic surface. Other plasma chemistries, including pure noble gas plasmas, are also used to increase the wettability of plastic surfaces.

Process Development

A series of surface treatment experiments was performed to evaluate the wetting properties of untreated LCP and the results of various surface treatments, in order to develop a satisfactory surface treating process to improve thin film adhesion. Three common surface treatment procedures were investigated: box oven dehydration, high vacuum Ar ion bombardment and low pressure oxygen plasma exposure. The surface treating process was evaluated by applying a drop of water to treated and untreated 50.8 μm thick low temperature LCP and then measuring the water contact angle. The same experiment was performed on both the matte and the shiny sides of the sample. The contact angle of the water drop is a good indicator of the wetting characteristics of the surface, with 0^o indicating a hydrophilic or wettable surface, and 90^o indicating a hydrophobic or nonwettable surface. The results of the series of surface treatment experiments indicated that dehydration decreases wettability, ion bombardment increases wettability and oxygen plasma exposure drastically increases wettability.

Adhesion layers are employed in the coating of plastics between the plastic surface and a noble metal layer. Certain metals have a particularly strong affinity for oxygen, including Al, Cr, Ni, and Ti, which tend to form oxides with oxygen based functional groups present on a polymeric surface, or with oxygen containing polymers. Since this application is biomedical, the metal selection criteria include biocompatibility of the deposited thin film metals. Therefore TiAu was selected, with Ti serving as the adhesion layer between the Au and the LCP surface. A series of experiments was performed to evaluate the adhesion strength of a 5000 Å E-beam deposited Ti layer on 50.8 μm thick low temperature LCP, after performing the previously investigated surface treatments. After Ti deposition, tape pull testing was performed to investigate Ti adhesion strength. The experiments consisted of dehydration (a 30 minute bake in a box oven at ambient atmosphere at 120^oC), oxygen plasma exposure (a 30 second exposure in a Matrix asher) and ion bombardment (a 2 minute exposure to Ar ion bombardment in an E-beam/ sputtering deposition system).

Surprisingly, the adhesion of the Ti was the highest with Ar ion bombardment, and not with the oxygen plasma exposure. Since Ti has a strong propensity for forming titanium oxide, it had been anticipated that the Ar ion bombardment of the LCP surface prior to Ti deposition (without breaking vacuum) would produce far worse

adhesion than either dehydrated LCP (mostly hydrophobic) or LCP exposed to oxygen plasma (extremely hydrophilic). Therefore a sample of 2mil thick low temperature LCP was dehydrated for 30 minutes at 120°C, then Ar ion bombarded for 2 minutes. The Ar ion bombardment should leave the LCP surface oxygen poor, with primarily C-C and C-H_x bonds, with crosslinking likely occurring. After ion bombardment, the samples were evaluated using X-ray photoelectron spectroscopy (XPS), versus dehydrated-only samples (matte and shiny). The results revealed that Ar ion bombardment reduced the concentration of surface bound oxygen from 13.8% to 7.7% on the shiny side and from 14.5% to 7.9% on the matte side. Therefore as expected, Ar ion bombardment does result in an oxygen poor surface.

A second test was then performed using a sample of 50.8 μm thick low temperature LCP that was Ar ion bombarded before deposition of 1000Å of Ti. Then auger electron spectroscopy (AES) and XPS surface analysis techniques were performed on the sample. The AES results showed that carbide formation was indicated by a distinct leading edge peak shape on the C(KLL, 272 eV) Auger peak. Such a leading edge is distinctive of carbide formation. For the XPS analysis, the C1s peak near ~ 285 eV is a doublet, indicating formation of C-C bonds and carbide bonds. The ratio of C-C to carbide bonds is roughly 50/50. This indicates that 50% of the thin film was converted to TiC during the deposition process at room temperature. The Gibbs free energy of an element with respect to another element is the propensity of the first element to bond with the second element, with the more negative the number meaning the higher the propensity. Ti forms TiC with a Gibbs free energy of approximately -43 kcal/g-mole at 298 K and goes to -39 kcal/g-mole at 1800 K [24]. Therefore it is not surprising that Ti adhered well to Ar ion bombarded LCP.

Next, an experiment was performed to evaluate the adhesion of Ti to Ar ion bombarded LCP over an extended period of time. Two samples (1 matte side and 1 shiny side) were fabricated using the standard dehydration and Ar ion bombardment procedures previously used, followed by a 5000 Å E-beam deposition of Ti. The samples were initially taped tested, then immersed in hot water (just below the boiling point) for 200 hours. Periodic tape testing was performed over the duration of the test. Both samples passed the tape testing throughout the duration of the experiment.

Therefore the selected thin film metallization process is a chemical cleaning of the LCP (to remove surface contaminants), followed by a 2 minute Ar ion surface ablation, directly followed by electron-beam evaporation of 500 Å Ti then 1000 Å Au. Tests were performed to determine the minimum feature size obtainable with this metallization. Contact photolithography was performed using a Carl Suss MA/BA6 frontside/backside mask aligner. The photoresist used was AZ5214, spun on at 3000RPM for 30s, yielding a thickness of approximately 1.2 μm. Standard Au and Ti wet etchants were used to pattern the metallization. The results indicated that 10 μm features had a high yield, 5 μm features had a fair yield and 3 μm features had a poor yield. Several factors contributed to the lower yields as the feature size shrinks below 10 μm. These include the nonplanar surface of the LCP, the propensity of LCP to attract contaminants to its surface, and the isotropic etching of wet etchants.

Fabrication of Demonstration Devices

Prototype interconnect devices were fabricated to demonstrate the use of LCP for this application. The basic device was designed to be compatible with probes such as the four-shank Michigan probe, presented in Figure 1. A drawing of the interconnect device is presented in Figure 2. It consists of a “head” section for connection to an external cable, a “tail” section for connection to the probe and a “bus” section connecting the head to the tail. The "tail" had 16 electrical attachment pads of approximately 75 μm by 300 μm. The electrical traces in the “tail” section were 10 μm wide with 10 μm spaces in between. The traces in the tail section merge to a parallel bus structure. There was a 165 μm gap down the center of the “bus”, where a channel could be micromachined into the LCP for various uses. One possible use would be for a fiber optic cable, if the probe required an optical interconnect. Another possible use would be for microfluidics, if the channel were capped. The “tail” section pads were arrayed to be compatible with a probe having a head approximately 2 mm by 2 mm, with an adjacent pad pitch of 150 μm. The “head” section of the interconnect was designed for convenient integration with system support electronics. It contains an array of 16 pads electrically connected to the pads at the tail of the device, plus an additional three pads for test purposes. The pad size was approximately 350 μm by 650 μm, with an adjacent pad pitch of 635 μm. The two rows of pads were separated by 990 μm. The head and tail were connected by an 11 mm long “bus” of 10 μm wide traces on a 20 μm pitch. Although batch fabricated, after device separation the prototype interconnect would appear as presented in Figure 2. The separated device head dimensions were 6.7 mm by 3 mm, the tail dimensions were 2.5 mm by 2.5 mm, and the interconnection bus was 10 mm by 0.56 mm.

Figure 2. A drawing of the separated prototype interconnect device.

50.8 μm thick LCP was used to fabricate prototype devices. After cleaning and dehydration, a 3 min Ar ion surface ablation was performed on the top surface. This was immediately followed by an electron beam deposition of 500 Å of Ti and then 1000 Å of Au. Then photolithography was performed on the TiAu layer (HMDS vapor prime, AZ5214 photoresist application, softbake, mask alignment, UV exposure, development, rinse, hardbake). After photolithography was completed, the exposed Ti and Au were etched away with wet etchants. Photoresist was then removed with acetone. Four photographs of the resulting devices are presented in Figures 3 through 6. The photograph of the three traces in Figure 6 was taken from the "bus" section. The design layout was for 10 μm wide lines and 10 μm wide spaces. The actual trace width was approximately 8 μm with space widths of approximately 12 μm. No process bias was added to the mask layout. Therefore width reduction of the traces was likely due to element width shrinkage during photolithography and undercutting during the wet Ti and Au etching processes.

Individual devices can be separated from the substrate by several methods, including wet or dry etching of the LCP between devices, or laser cutting. Prototype devices were separated from the substrate by encapsulating the devices and then dry etching through the exposed LCP substrate around the devices. In order to separate the devices on the substrate, the TiAu patterned substrate was dehydrated and placed back in the electron beam deposition system. After pump down, 0.5 μm of Al was deposited on the LCP substrate backside. A photoresist layer was deposited on the Al thin film and then patterned using a mask aligned to TiAu fiducials on the frontside of the substrate. Next, the exposed Al was wet etched and then the remaining photoresist was removed with acetone. The remaining Al pattern was then used as an LCP etch mask. The substrate was placed in a reactive ion etcher (RIE) and pumped down to approximately 20 mTorr.

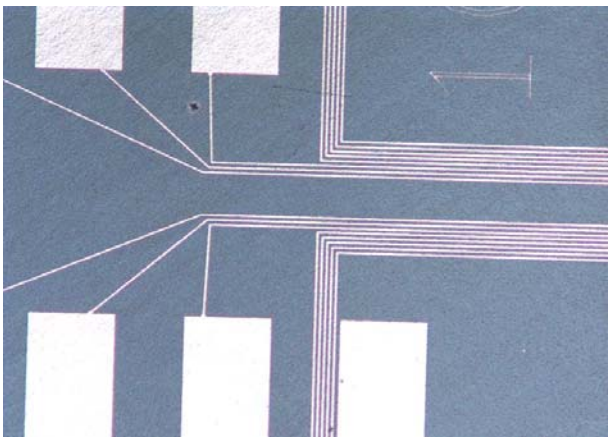

Figure 3. A photograph of the head section of a fabricated device.

A RIE gas chemistry of 85% O_2 and 15% CF_4, and an RF power of 350 W was used to etch through the exposed LCP, separating the prototype devices. After RIE, the remaining Al was removed with a wet Al etchant. A photograph of a separated prototype device is presented in Figure 7.

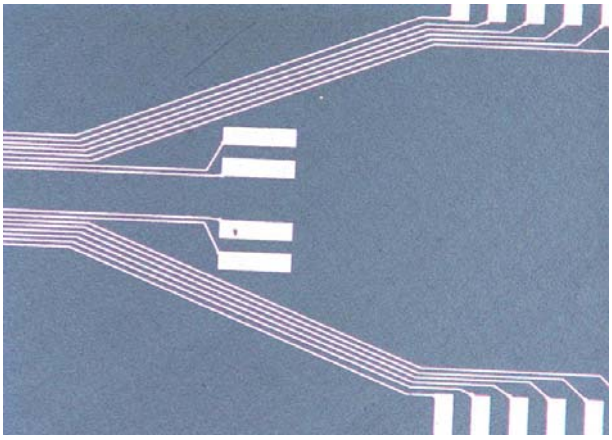

Figure 4. A photograph of the tail section of a fabricated device.

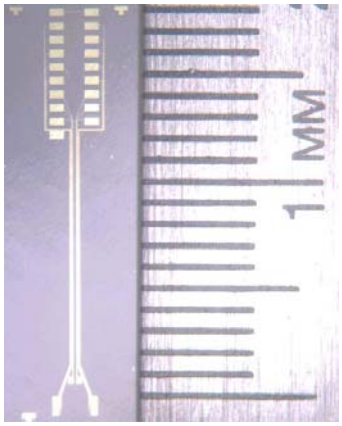

Figure 5. A photograph of a fabricated device.

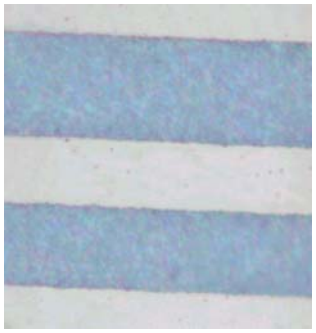

Figure 6. A Close-up photograph of three traces in the bus section.

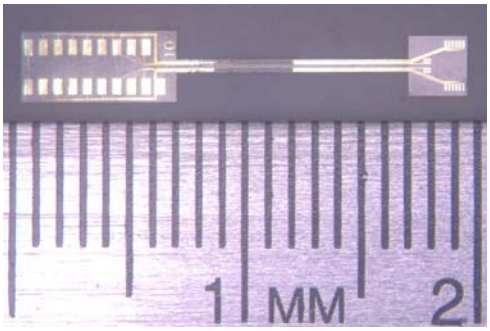

Figure 7. A photograph of a separated device.

Conclusions

A process was developed to realize fine pitch features in deposited thin films on LCP substrates. The resulting process was compatible with other micromachining processes developed for LCP, such as RIE. Good adhesion of the deposited thin film was a critical factor. It was discovered that Ti forms TiC with the surface of LCP if the Ti is deposited after Ar ion ablation of the LCP surface without breaking vacuum. Since LCP is biocompatible, TiAu was selected as the electrical interconnect metallization to realize a prototype interconnect for micromachined neural probes.

Prototype devices were fabricated. The results of this research, to date, indicate that LCP-based implantable devices may be a realistic solution for packaging micromachined neural probes in biomedical environments. The achieved feature sizes of these micromachined interconnects look very promising and they appear scalable to support hundreds of small electrodes, a significant increase over the current state of the art.

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