Flexible Miniature Ribbon Cables for Long-term Connection to Implantable Sensors

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Abstract

This paper describes the development of miniature, multi-lead ribbon cables for connecting implantable sensors to host electronics, either implanted or in the external world. The cables are flexible, electrically stable and biocompatible. Two technologies have been developed: one using polyimide (DuPont PI-2555) and the other using silicon as the support material. The present cables are less than 200 μm wide, are 10 to 20 μm thick and can be of arbitrary length (typically 1–2 cm). They can support as many leads as desired and can be bonded to the sensor substrate using flip-chip bonding techniques.

Introduction

The use of solid-state biomedical transducers for invasive and non-invasive patient monitoring has become increasingly feasible as such devices have been reduced in size, have become more reliable and have come to incorporate at least limited on-chip signal processing [1]. Invasive monitoring of patients has become an important focus for many biological and physiological research programs and for some clinical applications as well; however, sensor reliability remains the weakest link in the realization of such systems. The leads that connect the sensor to the outside world for the transmission of data and power are a major source of these reliability problems. Even when implantable telemetry systems are used, leads are usually required between the sensor and the electronics package. A common approach to solving these interconnect problems in the past has been to use fine wires, coated (after bonding) with either parylene or polyimide; however, parylene is difficult to deposit or etch selectively and polyimide is difficult to coat on fine wires. Neither approach has been adequate for use with 'floating' sensors such as microelectrode arrays in the brain [2]. This paper presents two technologies that have been developed for the fabrication of miniature, flexible, multi-lead ribbon cables, utilizing either polyimide or silicon as the support material. These cables have been designed for use with multichannel silicon substrate microprobes used for recording and stimulation of the central nervous system [2].

Requirements for a Chronic Interconnect Structure

There are several requirements that must be considered when designing an interconnect for long-term use *in vivo*. The materials used must be biocompatible and flexible, since many implanted sensors experience relatively large movements in the body, subjecting the connection to repeated flexing. Tethering forces must be minimized to prevent migration of the sensor. The interconnect must also be electrically stable, minimizing leakage between the tissue and the conducting leads as well as between leads. Table 1 describes some of the electrical interconnect requirements for a multichannel neural microprobe. Parameters are given for both passive (no on-chip circuitry) and active (with on-chip circuitry) arrays [3].

TABLE 1. Electrical requirements for interconnects to be used with multichannel silicon microprobe. Note that the shunt capacitance between the surrounding tissue and the conductive lead (C_{shunt}) can be relatively high, especially for the active probe. ($R_{end-end}$ = end-to-end resistance of a conductive lead, $C_{crosstalk}$ = capacitance between conductive leads, R_{shunt} = resistance between surrounding tissue and leads)

	$R_{end-end}$	$C_{crosstalk}$	C_{shunt}	R_{shunt}
Passive	Rec: ≤1 MΩ Stim: ≤10 kΩ	sub pF	≤4 pF	≥200 MΩ
Active	Pwr/Gnd: ≤1 kΩ	NA	NA/high	≥1 MΩ
	Data: ≤30 kΩ	NA	≤50 pF	≥300 kΩ

Design and Fabrication

The polyimide-based ribbon cables utilize DuPont's polyimide PI-2555 as a dielectric material

0924-4247/90/$3.50

to insulate metallic conductor lines as shown in Fig. 1. Polyimide has been shown to be a very good insulator against ionic conduction [4] and is very flexible. The bottom polyimide layer is first deposited by spin coating it onto a 4 μm thick sacrificial aluminum film, which has been evaporated on a silicon wafer, and is then fully cured (Fig. 2(a)). The conductor metal (Cr–Au–Cr or Ti–Ta–Ti) is then deposited and patterned using reactive ion beaming etching. If additional protection is needed, the conductor material can be sandwiched between two layers of sputtered silicon nitride, which is an excellent barrier against both moisture and ionic contaminants. The top polyimide layer is now deposited and fully cured. The two polyimide layers are then patterned using oxygen plasma with an aluminum mask until the sacrificial aluminum in the field areas is exposed (Fig. 2(b)). If desired, solder or gold bumps can be formed in the bonding pad areas for later connection to the sensor substrate (Fig. 2(c)). The finished cables are then released by undercutting the aluminum film in an acid etch. The process uses only three masks and all dry chemistry except for the final release of the cables.

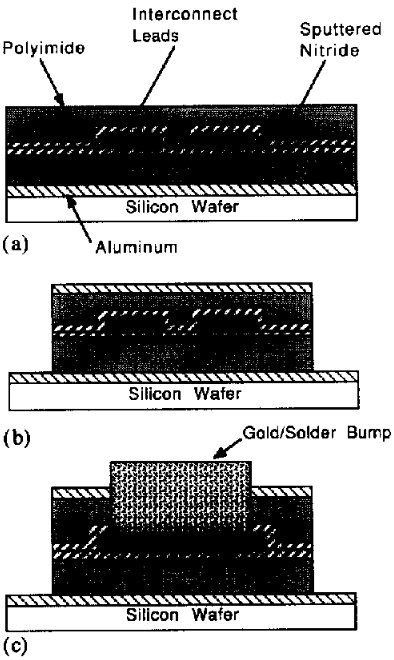

Fig. 2. (a)–(c) Fabrication of a polyimide cable.

The silicon-based cables use a boron-diffused silicon substrate to support the conductors as shown in Fig. 3. The conductors are insulated between multiple layers of silicon dioxide and silicon nitride, deposited using PECVD and LPCVD techniques (Fig. 3(a)). After patterning the top dielectric, the cables are covered with a metallic shield, such as tantalum, fully shielding the conductor lines (Fig. 3(b)). Finally, openings to the conductors are made and gold or solder bumps are formed. The cables are then released in EDP, which etches the undoped substrate but does not attack tantalum or any of the other materials used. These cables are shielded on top and bottom by grounded conductive layers, thus effectively creating a multiconductor coaxial cable. Both the silicon and the tantalum are excellent barriers to moisture and ionic contaminants. Following their release, the cables are flipped over and bonded to pads on the substrate by either solder reflow or thermocompression bonding. The bonded areas are then encapsulated by additional layers of polyimide.

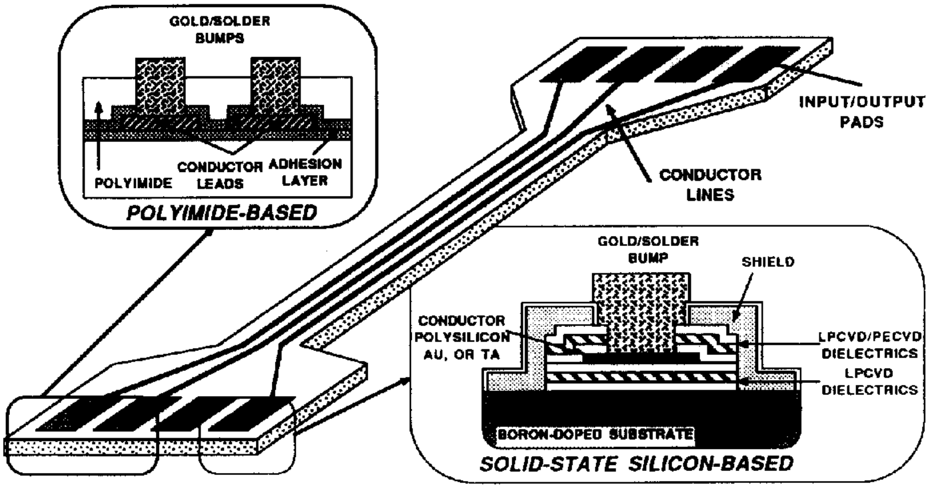

Fig. 1. Cross-sectional views of polyimide- and silicon-based ribbon cables.

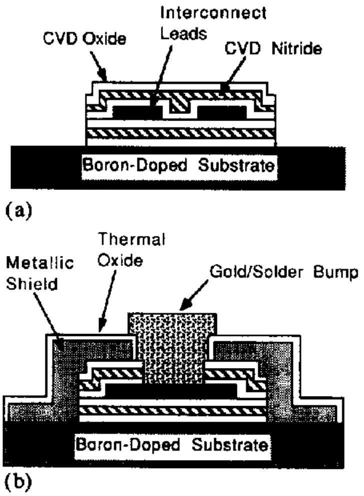

Fig. 3. (a)–(b) Fabrication of a silicon cable.

Process Results and Discussion

Figure 4 shows a photograph of some polyimide cables. The leads are 20 μm wide and are composed of 400 nm of tantalum sandwiched between top and bottom titanium films for improved adhesion. The polyimide cables are quite flexible, and when laid out in a serpentine shape to conserve mask area they can be expanded to lengths of several centimeters. The measured lead resistance is about 4 kΩ/cm for Ta leads and 100 Ω/cm for gold, with a shunt capacitance of 1.6 pF/cm and a crosstalk capacitance of <10 fF/cm. These values are within the accepted limits for both passive and active probes as described by Table 1. These polyimide ribbon cables have been soaked passively, i.e., no electrical stress, for over two months in buffered saline and have shown no sign of degradation or delamination of the polyimide. A soak structure has been developed for soaking the cables in saline while under 5 V electrical stess. Long-term soaking of polyimide using interdigitated comb structures has produced cross-comb leakage levels that remain stable around 25 pA and through-insulation leakage levels of less than 1 pA (<1 fF/μm^2) after over three months of soaking under 5 V electrical stress [5]. It is therefore believed that polyimide cables should provide an adequate interconnect for both active and passive sensors for periods of months or more. Long-term electrical and mechanical testing of the cables is presently under way.

The silicon cables are also very flexible, especially when the silicon thickness is less than 10 μm, as demonstrated in Fig. 5. These cables can be easily bent into a full circle. The measured lead resistance is about 4 kΩ/cm for Ta leads and 5–10 kΩ/cm for polysilicon, with a shunt capacitance of 5–10 pF/cm and an interlead capacitance of <10 fF/cm. Referring to Table 1, polysilicon would probably not be a good lead material, at least for the power and ground leads of the active

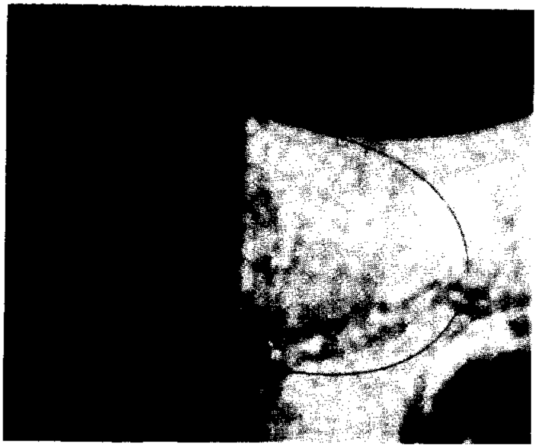

Fig. 5. A 15 μm thick silicon-based ribbon cable bent in a circle to illustrate its flexibility.

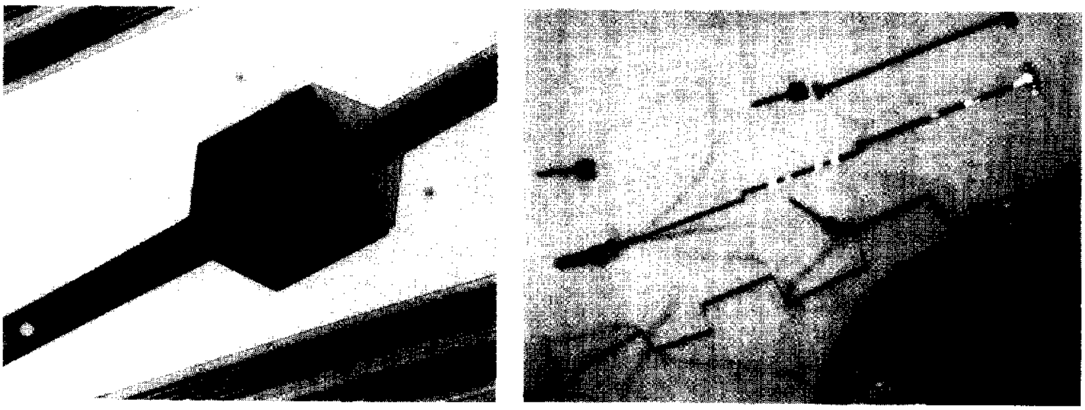

Fig. 4. Polyimide ribbon cables with tantalum interconnect leads. Flexibility permits the cables to be stretched to various lengths.

probe, due to its relatively high end-to-end resistance. It should also be noted that the shunt capacitance of the silicon cables is on the high end of that required for passive probes; however, they should be very useful with active probes. Polysilicon combs coated with the same dielectrics as the silicon cables have maintained sub-picoamp cross- and through-dielectric leakage currents after more than one month of exposure to buffered saline under 5 V bias. Soak tests are currently being performed on silicon cables under 5 V bias. Results so far are similar to those obtained with the dielectric-coated combs.

The biocompatibility of polyimide has been studied in several neural structures [6], with the results suggesting that polyimide, once fully cured, is biocompatible. The biocompatibility of multichannel silicon microprobes has been studied in the cochlear nucleus of guinea pigs. The probes were well tolerated by the surrounding tissue.

Acknowledgements

This work was supported by the National Institutes of Health under contract NIH-NINCDS-NO1-NS-7-2397. The authors would like to thank Drs F. T. Hambrecht and W. Heetderks of the Neural Prosthesis Program, NINDS, for their encouragement and guidance in this work.

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