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Abstract (Doctor)

Title of Thesis	Stretchable Kirigami devices for biological applications

Approx. 800 words

Technologies of recording biological signals from brain, heart, and muscle are expected to be used for the treatment of psychiatric and neurological disorders. These technologies can also be used for restoring lost functions, such as brain–machine interface and human–machine interface.

Microscale needle-electrodes and film electrodes are commonly used for the recording of biological signals from tissues. Intimate integration between electrical devices and soft biological tissues can be achieved while device material is biocompatibility and the material's mechanical characteristics (e.g. Young's modulus) are similar to those of the biological tissues.

To this purpose, numerous types of flexible and stretchable devices have been developed. Conventional flexible devices are fabricated using a polymeric material, however the Young's modulus is approximately six orders of magnitude higher than those of the biological tissues (e.g. brain and muscle). In addition, Young's moduli of elastomer materials used in stretchable devices are large compared to those of the biological tissues. Therefore, there is a possibility that these mismatches may induce tissue damage and malfunction. Moreover, the mismatch of Young's modulus between soft elastomer materials and rigid device components (e.g. transistors and interconnections) may be the cause of failure of the device components, due to the large strain applied to the stretchable device.

In this study, a low invasive neural interface device using a Kirigami structure is proposed for biological applications. The aim is to achieve an intimate integration between electrical devices and soft biological tissues. A remarkable feature of the Kirigami structure is its high stretchability, which includes a high strain ratio and low effective modulus. Moreover, the mechanical characteristics of the Kirigami structure can be designed (e.g. slit length and gap of the Kirigami structure). In contrast, characteristics of conventional stretchable devices depend on the intrinsic characteristics of the materials used.

The stretchability and recording capability of the Kirigami device has been confirmed as a Kirigami bioprobe device. A displacement model of the Kirigami structure was derived to estimate the deformation of the Kirigami structure, which depends on the applied force (or stress). In addition, the stress distribution in a Kirigami structure was calculated. The displacement model and the stress distribution results provide an effective and robust method of designing a Kirigami device. A Kirigami device was designed and fabricated for the applications to electrocorticogram (ECoG) and electrocardiogram (ECG) signal recordings from mice. The fabrication process was based on parylene-microelectromechanical systems (MEMS), which includes embedded platinum layer playing roles in microelectrode and device interconnection. The fabricated Kirigami bioprobe device exhibited the stability of its electrical impedance with the device stretching, and the mechanical characteristics comparable to the soft biological tissues was confirmed. In addition, the durability of the Kirigami device was confirmed during a 4,000-cycle strain test. The recording capability of the fabricated Kirigami device was confirmed in the ECoG and ECG signal recordings using

mice. These experiments indicated the ability of the Kirigami device to achieve the intimate integration with biological tissues. However, the fabricated Kirigami device caused displacement on the biological tissues, which show their large deformation.

To achieve the device's stability on deformable biological, such as heart and muscle, a donut-shaped Kirigami device was proposed. The donut-shaped Kirigami device exhibited the stability on the deformable tissue surface, as confirmed in the displacement test using deformable balloon instead of real biological tissues. The displacement test results exhibit five–to–eight times less displacement, compared to the displacement caused by the other sheet-type Kirigami device which were used in ECoG and ECG applications. The recording capability and stability of the fabricated donut-shaped Kirigami device were also confirmed in the biological signal recordings from large deformable tissues, including heart and hind limb of mice.

Another challenge faced by the Kirigami device was the smooth integration of its rigid components in the stretchable Kirigami structures, in order to achieve the device's multifunctionality. An optoelectrical Kirigami device was proposed for the treatment of heart disease. The proposed device includes arrays of light emitting diodes (LED) for optical stimulation to and microelectrodes for ECG signal recording from the light-sensitive proteins expressed heart of a mouse. Regarding characterizations of the optoelectrical Kirigami device, no significant changes in resistance of the device interconnections during the Kirigami stretching. Moreover, there was no change in the resistance during the durability test for 300–400 cycles. It was also confirmed that the latch structures showed high enough fixation force to enable the device's fixation on the heart tissue. The LED functionality test revealed a yield of 100%. These results successfully demonstrated a highly stretchable device suitable for cardiac tissue defibrillation using optogenetic stimulation.

In summary, these results indicate the capability of the Kirigami device as the appropriate platform of low invasive neural interface devices. It is believed that the features of the Kirigami device can be extended to applications involving the integration of electrical components with biological tissues. Moreover, the high stretchability, stability, and unique transformation of the Kirigami structure will expand possibilities for stretchable electronics including sensors and actuators.