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Psychological tactile sensor structure based on piezoelectric nanowire cell arrays

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To produce artificial psychological feeling, especially 'pain', electrical mimic structure of human skin has been studied. Touch by a sharp and a blunt object induce figurative different deformations of the skin of human fingers. Imitating this phenomenon, the skin mimic device employing the piezoelectric nanowire sensor arrays can generate the electrical 'pain' signal with signal processing when a pen cap presses the device. The electrical 'pain' signal is expected to enhance the protection mechanism of android robot or mobile phone from harsh environment.

Recently, artificial tactile sensors have been studied in attempts to mimic the human sense of touch for various applications, from the simple input function of mobile devices to the complicated finger systems of android robots [1-8]. Unfortunately, most touch sensors that have been developed so far simply detect pressure without the generation of psychological feelings, or focus on achieving grip control, to hold an egg or some other fragile object. For human beings, psychological feelings such as softness, roughness or pain are quite important for interactions with other humans and objects. Furthermore, pain is an essential feeling that protects the human body from sharp objects such as a knife, needle, or nail. Therefore, if we can develop an artificial tactile sensor, which can generate an electrical pain signal, an android robot hand or a mobile phone touch display can be better protected from contact with sharp objects or some harsh environments.

Here, we report tactile sensor arrays and a signal processing based on ZnO piezoelectric nanowires to produce feelings of sensed artificial psychological pain. Tactile sensors based on ZnO piezoelectric materials have several advantages, such as being self-powered, highly sensitive, high resolution, multi touch availability, and simple design. To get high sensitivity of touch, the piezoelectric characteristics of ZnO nanowires have been studied with various metal electrodes, including the effects of nanowire structural factors. By signal processing of the detected signals based on a pattern analysis and its pressure level, the proposed artificial tactile sensor structure was able to successfully produce an electrical pain signal from the touch of a sharp object.

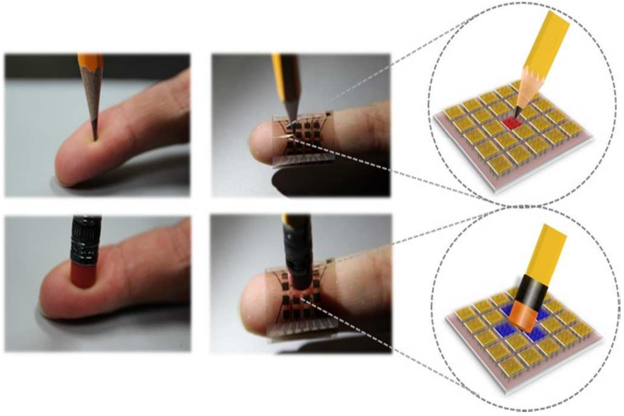

Fig.1 Schematic illustration of how to produce an electrical 'pain' signal by touch sensor arrays. The pressure levels and the distribution shape of activated cells induce 'pain' or 'smooth' feeling signal.

Figure 1 shows the schematic illustration of how to produce electrical pain signal using our suggested device structure. As shown in the figure, the skin of a human finger deforms differently according to the shape of the touching object: a pencil lead produces a high pressure on a very small area of skin, whereas the pencil eraser deforms a larger skin area. Because humans have several various types of touch receptors in the skin, and the signals from those receptors can arouse a 'pain' signal as well as a 'soft' and a 'rough' feeling in the nervous system [9,10], it is not easy to mimic a human system perfectly using a simple artificial device design. However, if a proper electro-mechanical structure design can mimic the figurative different deformations, it can produce a simple pain signal. . Although it is just a simple pain signal, it can be

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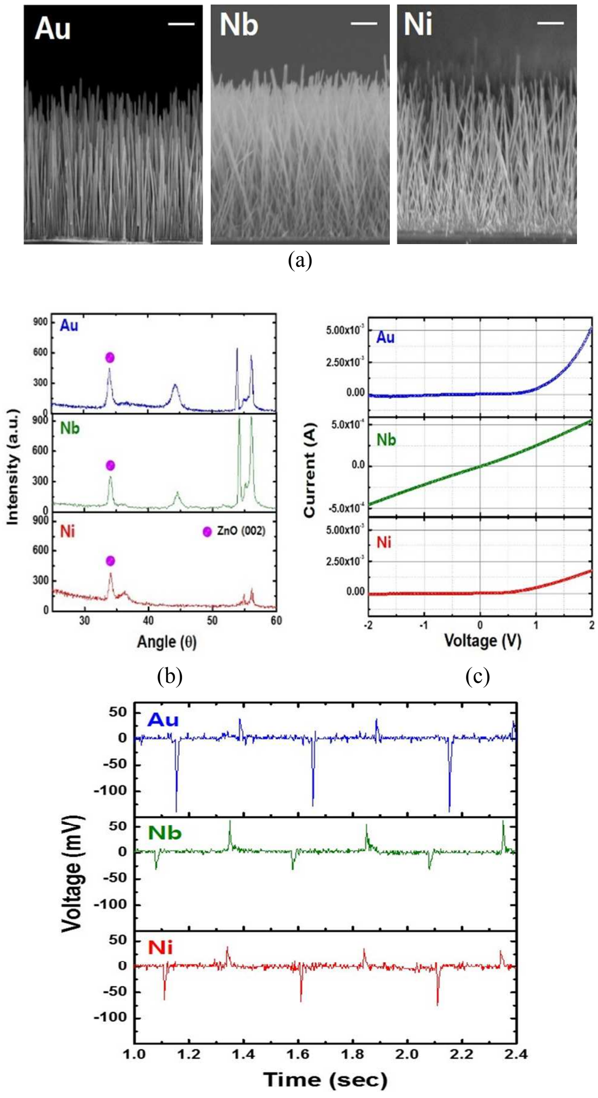
useful in protecting the device from some harsh objects. To achieve this goal, electromechanical pressure sensor array structures and signal processing approaches are suggested. By distributing a number of active sensors, a sensor array device can detect different pressure levels, such as the prick of a pencil lead or the press of a pencil eraser in a manner similar to the deformation of human skin. When the system is pricked with the pencil lead, a single or few cells will be activated with a high pressure signal; but in the case of the pencil eraser, multiple touch pressure signals will be produced by the centre and the neighbouring cells (Fig.1 right side illustration). By signal processing of the detected signals based on a pattern analysis and a threshold pressure limit, an artificial pain signal can be generated in the case of a pencil lead.



(a)

(b) (c)

(d)

Fig.2 ZnO nanowires grown on various metal layers. (a) SEM image of ZnO nanowire on Au, Nb, Ni. The scale bar corresponds to 1μm (b) XRD analysis results of ZnO seed layer on various metals (c) I-V characteristics with a different metal layers (d) The piezoelectric voltage of an ZnO sensor array using different metal bottom electrode. Applied pressure level is 25kPa.

For pressure sensor arrays, various principles can be applied to detect pressure levels. Resistive and the capacitive type touch sensor have been recently developed and widely adopted in smart phones and tablet PCs [11,12]. Although those approaches have various merits, the simple matrix resistive type is limited for multi-touch applications due to cross-talk issue, and the capacitive type has low pressure sensitivity, which can be barriers to our suggested working principle. Among other mechanisms, a piezoelectric sensor structure is a good candidate for our proposed system, because it has good spatial resolution, multi-touch ability, and excellent pressure sensitivity. Moreover, since it can produce electrical power or signal by itself due to the piezoelectric effect, which consumes no power, the mechanism is quite ideal for an android robot or smart phone which needs a battery to work independently. Pb[Zr,Ti]O_3 (PZT) has been well known as a high piezoelectric coefficient material and studied widely. However, the high processing temperature of PZT (~600°C) limits its use with flexible substrates because most flexible substrates are vulnerable to a high heat environment [13]. To apply the sensor array concept to the finger of an android robot or wearable device, the device substrate should also be flexible. Considering various aspects of device structure and characteristics, ZnO nanowire was selected for our device structure. ZnO nanowires are easily grown by hydro-thermal process below 90°C so that the process can be applied to most flexible substrates, and the cost of the fabrication process is lower than that of vacuum deposition processes. Also, unlike the low piezoelectric coefficient of ZnO bulk film, the ZnO nanowire structure has a relatively high piezoelectric coefficient due to the structural confinement of the nanowires in the radial direction. Therefore, ZnO nanowire was deliberately selected for use in the proposed high sensitivity pressure detector system. [14-16]

To enhance the signal to noise ratio of the ZnO nanowire pressure sensor structure, the characteristics of the piezoelectric effect were studied with various metal electrodes. Under applied force, a net dipole moment is induced in a ZnO nanowire. Due to the net dipole moment, electrical charges accumulate on the top and the bottom electrodes of the sensor structure, which results in the flow of piezoelectric current. Since ZnO is a wide band gap semiconductor [17,18], an electrical barrier structure between the ZnO nanowire and metal electrode can improve the current level by preventing hole-electron recombination at the boundary of the electrodes. A Schottky barrier provides the appropriate solution due to its simple fabrication process. For comparison, three types of electrode, Au, Nb, and Ni, were formed as the bottom electrodes of a device structure. The hydrothermal method was employed to grow ZnO nanowires on those metal layers. The nutrient solution was composed of a 1:1 ratio of zinc nitrate and hexamethylene-tetramine (HMTA). The process temperature was set at 90°C. As shown in Fig 2.a, ZnO nanowires grew well on the metal electrodes with slightly different forms of growth. All cases of ZnO nanowire are similar in length and diameter. However, the vertical alignment of the nanowires is a little different. The ZnO nanowires on Au layer are aligned well vertically, whereas some nanowires on Nb and Ni layer are tilted slightly. Considering the vector field of the electrical dipole moment induced by the piezoelectric effect, good vertical alignment can generate a higher electrical signal. Thin ZnO film (50 nm) formed by RF magnetron sputtering system at room temperature was used as a seed layer for the growth of the ZnO nanowires. The working pressure and the power of sputtering are 1×10^{-2} torr and 200W, respectively. As shown in the XRD analyses of the seed layers on various metal layers, the seed crystals in ZnO film on Au layer have a higher level of preferred orientation to the (002) direction (Fig. 2.b), which results in the nanowires on Au layer having a higher probability of growing vertically. The calculated Schottky barrier height of Au, Nb, and Ni are 0.9eV, 0.1eV, and 0.81eV, respectively. The current-voltage (I-V) curve of those three metals employed as bottom electrode correspond well to the barrier heights (Fig.2.c). Au and Ni cases show an asymmetric I - V characteristic due to Schottky barrier formation, whereas, Nb layer forms an ohmic-like contact situation.

To measure the piezoelectric characteristics of ZnO nanowire on various metal layers, an ITO coated PEN film was put on the grown ZnO nanowires as an upper electrode. The sensor structure employing Au shows the highest signal to noise ratio (Fig. 2.c). This is reasonable taking the Schottky barrier height and the vertical alignment of nanowires into account. For a bulk cylindrical piezoelectric generator, induced voltage is simply expressed in terms of applied force. If the applied stress is T, then the induced polarization P is

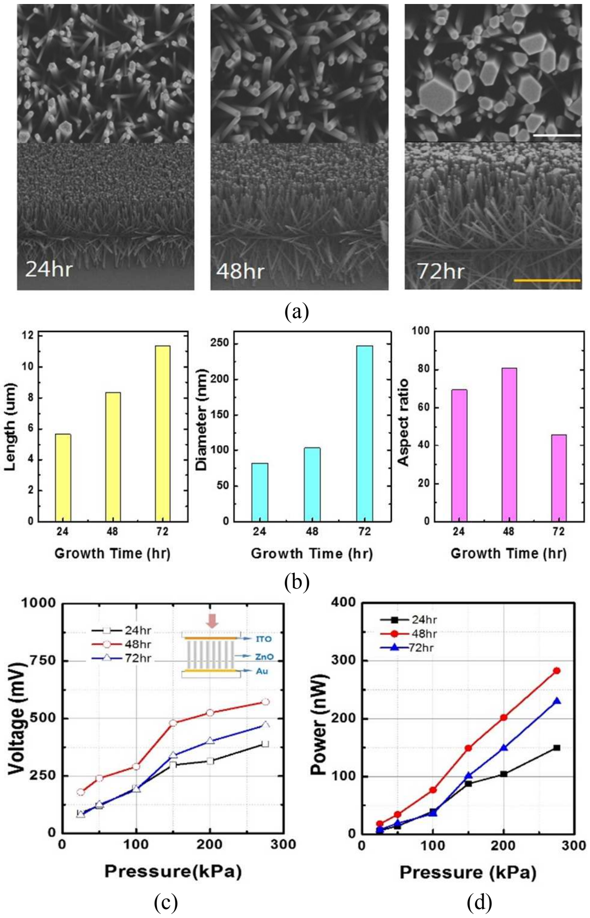
$$P = dT = d\frac{F}{A} \tag{1}$$

where d is the piezoelectric coefficient, F is force and A is the dimension of the generator.

Induced polarization P leads to induced surface polarization charges given by $Q = AP$. If C is capacitance, then induced voltage is

$$\mathrm{V} = \frac{Q}{C} = \frac{AP}{\left[\frac{\varepsilon_0\varepsilon_r A}{L}\right]} = \frac{LP}{\varepsilon_0\varepsilon_r} = \frac{L\left[d\frac{F}{A}\right]}{\varepsilon_0\varepsilon_r} = \frac{dLF}{\varepsilon_0\varepsilon_r A} \tag{2}$$

where L, ε_0, and ε_r is the length of the cylinder, the absolute permittivity, and the dielectric constant of the piezoelectric material, respectively. Considering the characteristics of the ZnO nanowire piezoelectric structure (d~10 x 10^{-12}mV^{-1}, L~7 μ m, F/A~25kN/m^2, ε_r ~7.40[12]), the calculated induced voltage is about 26.7mV. However, the real voltage induced by ZnO nanowires on the Au layer was about 120mV. As mentioned previously, due to its structural confinement, a wire that has a diameter in the nanometer range will result in much higher piezoelectric voltage. Although the ZnO nanowire structure on Nb and Ni layers shows a smaller induced voltage signal, we think that the level is also sufficient for application in a pressure sensor structure. Two signals are produced by a piezoelectric system that are useful for the sensing device. One is induced when a pressure is applied by an object, and its release results in the other signal. The signal produced by the release is also important because the time difference between the applied pressure signal and the release signal equals the duration of time that pressure is applied by the object. Although the structure does not directly measure the level of static force, due to this working principle, it has an important advantage for sensing touch, and dynamic force sensing, because the electrical power is proportional to the strain velocity. If an object presses the sensor structure for a long time, the charge carriers on the surface of the metal electrodes can disappear due to hole-electron recombination or thermal agitation. To prevent hole-electron recombination in the ZnO nanowire sensor structure, the intrinsic properties of the ZnO nanowire and Schottky barrier height are quite important.



(a)

(b)

(c) (d)

Fig.3 Pressure sensitivity with various structural dimension of ZnO nanowire (a) SEM images of ZnO nanowires grown for 24hr, 48hr, and 72hr; The white and the yellow scale bar correspond to 1μm and 10μm, respectively. (b) Dimensional values of ZnO nanowire by different growth time; average length, average diameter, and aspect ratio of length to diameter (c) Peak voltage generated by various pressure (d) Electrical power produced by pressure.

Figure 3 shows the pressure sensitivity with various ZnO nanowire structural dimensions. Because the growth rate of the nanowire in the radial direction is quite slower than that of the longitudinal direction, long growth time, which results in a longer ZnO nanowire, does not guarantee higher sensitivity due to an increase in diameter. To find the optimal ZnO structural dimensions, pressure sensitivity was measured with three different ZnO nanowire growth times. With increasing growth times up to 72 hr, the length of the nanowires increased; however, the growth rate decreased slightly. Due to an increase in radial direction growth, the 48 hr growth condition shows the highest aspect ratio of length to diameter (Fig. 3. a,b). From these structural differences, signal levels, represented by piezoelectric voltage are changed. As expected, the 48 hr grown ZnO nanowires with the highest structural aspect ratio lead to better pressure sensitivity over the entire pressure range.

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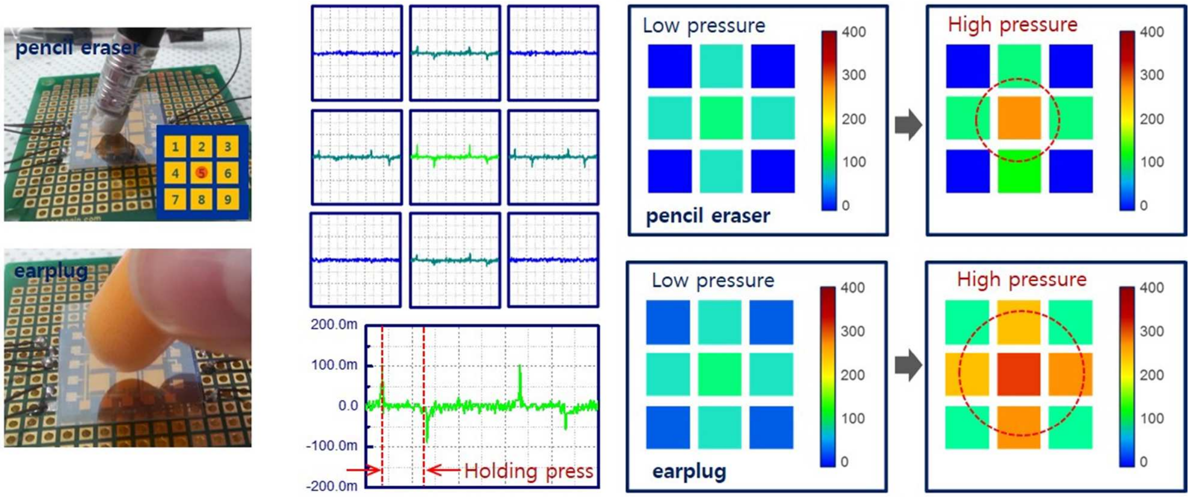

(a) (b) (c)

Fig.4 Pressure level images of the touch of pencil eraser and earplug with different pressure level (a) photo image of touch situation by pencil eraser and earplug (b) piezoelectric voltages of 9cells by the touch of pencil eraser (top) and the enlarged graph of the centre cell (bottom) at low pressure touch (c) visual image of piezoelectric voltages depended on the touch object and the pressure level. The yellowish green colour matches approximately 100mV

Although the electrical voltage level produced by the all case of ZnO nanowire cells is enough to be detected by a general electrical sensing circuit in the low pressure range, considering power consumption, reliability and durability, the 48 hr growth time was determined to be an optimal condition for the psychological tactile sensor structure. Since the generated voltage levels are changed within test pressure levels without a saturation, the ZnO nanowire sensor structure is quite appropriate to the pressure sensor application. At the 72 hr growth condition, the SEM image shows a large deviation of nanowire diameters. A few nanowires have abnormal diameters, whereas most of the nanowires show a similar diameter or are slightly thicker than that of 48 hr. For that reason, even though the average aspect ratio is lower than that of the 24 hr growth condition, the 72 hr grown ZnO nanowire structure shows better voltage level than the 24 hr growth condition. The produced power level is almost higher than 10nW, so that it is possible to detect the signal level without any other power consumption. It can be an important merit for the applications such like an android robot and a smart phone which needs to work independently without power supplying line connection.

To prove the concept of a psychological tactile sensor, 3 x 3 cell arrays employing ZnO nanowires were fabricated. As the top electrode of the sensor structure, Au thin film electrodes were formed on a PEN substrate, which resulted in aligned ZnO nanowires. Blunt objects, such as a pencil eraser and earplug, were used to touch the centre of the cell arrays with different pressures, as shown in Fig. 4a. Within pressure states, the electrical signals produced by the deformation of the ZnO nanowires in all cells was detected by the sensing system (Fig.4.b) and the levels changed the different colours on the visual image form by simple image processing (Fig.4.c). The touch of the pencil eraser with low pressure creates contact points on the centre area so that the centre cell (~100mV) and other neighbouring cells (~50mV) produce piezoelectric signals, whereas there are no signals detected for the other 4 corner cells since they are not in contact. The time between the red lines on the enlarged piezoelectric voltage graph of cell 5 indicates the length of time the pressure of the pencil eraser was maintained (Fig. 4.b). With a piezoelectric material, no signal is generated when pressure is maintained over time at the same level. However, since the initial and the final touches induce current flows in the circuit system, we can estimate whether some object is still pressed onto the system or has detached from the device. When the pressure level is increased, the piezoelectric signals are also increased and the centre cell colours are changed to yellowish green and orange on the detection image. However, the other 4 corner cells that are not contacted do not generate any electrical power and keep their blue colour state. For the centre cell, at the high pressure level, the piezoelectric voltage is about 250mV. It should be noted that if only voltage was selected as the threshold evaluation factor to indicate a ‘pain’ signal from the device, and its level was above 200mV, the sensing device would produce a ‘pain’ signal even with the high pressure of an eraser, even though people do not feel pain for the same situation normally.

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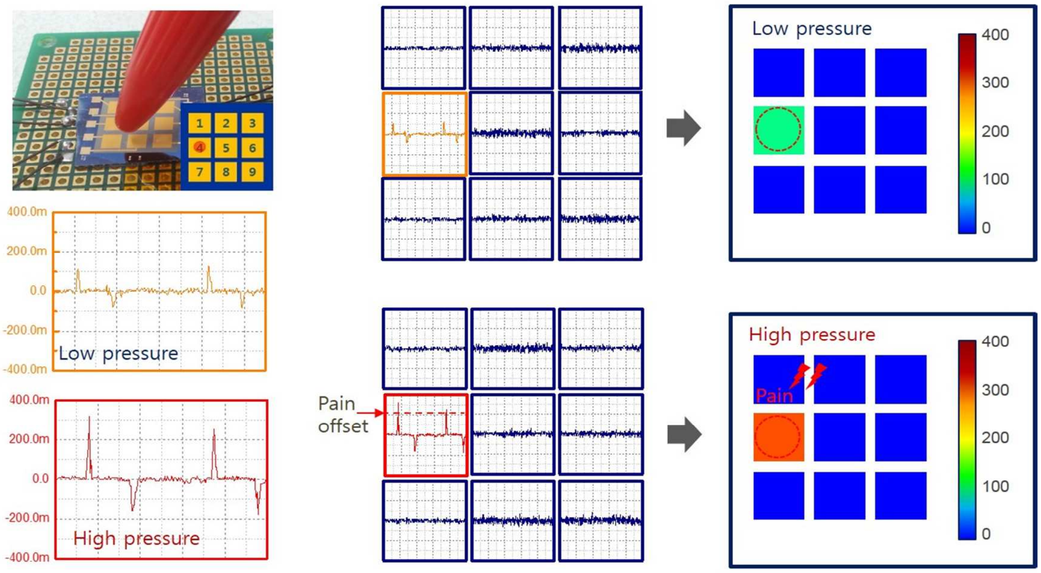

Fig.5 Pressure level visual images by the touch of pen cap with different pressure level. The cap presses the cell 4 position (photo image). Among 9 cells , the cell 4 only generates the piezoelectric signal (middle graph). The enlarged graph for cell 4 shows the piezoelectric voltage is changed with pressure level (left graph). The visual image formed by signal process shows clearly the active cell position with signal level.

This is not the case with our system, because the device does not generate a ‘pain’ warning simply based on an electrical signal exceeding the threshold limit: signals from the other sensors in the array, and their number and distribution, are also part of the evaluation factor of the ‘pain’ feeling. Based on the sensing cell distribution and the signal levels, the system roughly recognizes the shape of a touching object, and the pressure level precisely. The signal detections of the other 4 edge cells provides the device with information that the touching object is not sharp like a needle. With the earplug, the object is bigger and much softer than the eraser, and so it contacts a larger area with the same pressure level. The different characteristics of the object can be easily detected by the visual image processing result. All 9 cells have their own signals due to the touch of earplug. Higher contact pressure generates higher electrical signals from the 5 centre region cells than the threshold limit voltage. However, due to the detective cell distribution, there is no ‘pain’ signal, either. The red colour rings on the visual images mean that the potential of the inside ring is higher than 100 mV. The ring area is quite well matched with the area contacted by the pencil eraser and earplug. Therefore, we can estimate the shape of an object inversely by the artificial tactile sensor structure as well.

Figure 5 shows how to produce the ‘pain’ feeling with the touch of a pen cap. When the pen cap, which has a sharp shape, pressed the device with low pressure, specifically at cell position 4, only that cell generated a piezoelectric signal. The detection level is similar to the level when the pencil eraser presses the device with low pressure. Since the pen cap only touches cell 4 due to its sharp shape, the other cells do not generate any electrical signals. However, the signal level is lower than the set threshold voltage (>200mV), so that the ‘pain’ signal is not produced. With the increasing pressure level of the pen cap, the piezoelectric voltage of cell 4 is increased about 300 mV, whereas other cells continue to generate no signal, unlike when touched by a pencil eraser or earplug. The visual images clearly show the touch situation, which differs from the touch of a pencil eraser or earplug. Only cell 4 has a change of colour, from bluish-green to orange. With respect to the two evaluation factors, signal level and sensing cell distribution, the system recognizes that a sharp object is stabbing the device with high force. Consequently, the device produces an electrical ‘pain’ warning signal. If the artificial tactile sensor system is applied to an android robot or mobile phone, that electrical ‘pain’ signal could drive some protective mechanism in response to the touch of sharp objects. When humans touch their finger lightly with a needle, we do not have a ‘pain’ feeling, however, with greater force, we feel ‘pain’ immediately. Therefore the phenomenon to induce the ‘pain’ feeling in the artificial device is quite similar to the human feeling situation. Because the response time of the ZnO nanowire sensor arrays is quite fast, the device structure is quite appropriate for use in the psychological tactile sensor and its various applications.

Conclusions

To produce artificial psychological feelings, we tried to develop tactile sensor arrays and a signal processing based on ZnO piezoelectric nanowires. The sensors based on piezoelectric materials have several advantages such as self-powered, high resolution, multi touch, and simple design. Pressure value was evaluated easily from produced electrical power by ZnO nanowire structure. By array design of self-powered tactile sensor, the pressure level and the figuration of touch object were perceived. In the respect of two evaluation factors, signal level and sensing cell distribution, the system recognized that the sharp object stabbed the device with high force, and then, the device produced an electrical 'pain' warning signal. This suggested design and concept can induce various new applications for electrical devices and robot industry.

Notes and references

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