

# Magnetically, Vertically-Aligned Conducting Ferromagnetic Particles for Electrical and Heat Conduction in Stretchable Electronics

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## Abstract

*My group spent several years to develop sensor and bonding materials based on composites with conducting ferromagnetic particles for flexible/stretchable display and soft electronic skin applications. Vertically aligned conductive particles provides excellent electrical conducting paths without electrical short in lateral direction up to 10 micro meter scale and pressure sensitive resistive paths up to 100 dpi resolution even without lateral patterning. In addition, such composites can be used for temperature sensing material because they change in their physical dimensions with temperature, leading to resistance change with temperature. In this invited talk, my group's most recent result in micro scale display integration and high-resolution sensor implementation based on the composite material that we developed.*

## Author Keywords

flexible/stretchable display; stretchable electronics; wearable electronics; soft electronic skin; soft elastomer; ferromagnetic particles; vertically-aligned; magnetic field

## 1. Introduction

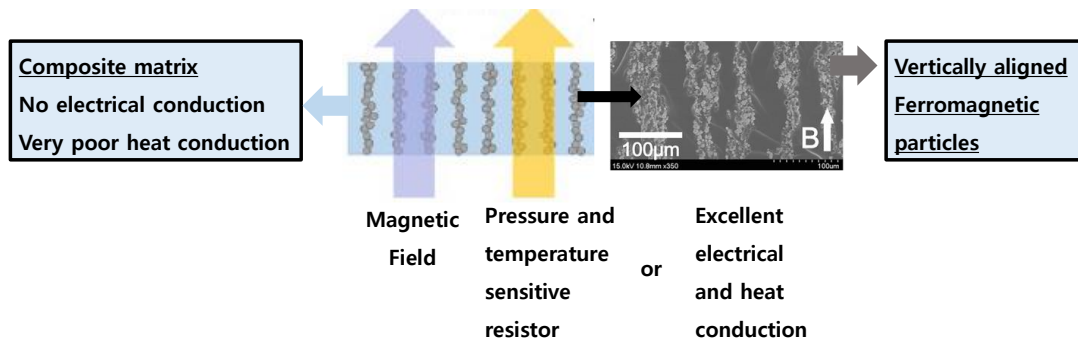
Composite with conducting particles has been widely used in flexible and stretchable electronics including displays and soft electronic skin sensors. Although such composite has been used as flexible and stretchable electrodes, physical dimension change of the composite by external force or temperature leads to resistance change in general. Therefore, it is an excellent material candidate for resistive sensors. If the conducting particles can be aligned or patterned by magnetic field, an electronic sensor skin sheet where resistive sensing materials are fully embedded in a patterned form can be fabricated [1][2]. In addition, since the

conducting particles are typically good for heat conduction, patterned embedded dense particles can be also used for localized heat conduction in stretchable thermoelectric batteries [3][4]. When high conducting particles such as silver-coated-nickel particles or silver-coated-iron particles are used in the composite materials, they provide excellent electrical conducting only in a vertical direction when they are exposed to a vertical magnetic field during curing process of composite materials [5][6][7]. In this invited talk, details of various functions (Figure 1) of the conducting ferromagnetic particles in electrodes, bonder, heat conduction, via, pressure/temperature sensor applications.

## 2. Results and Discussion

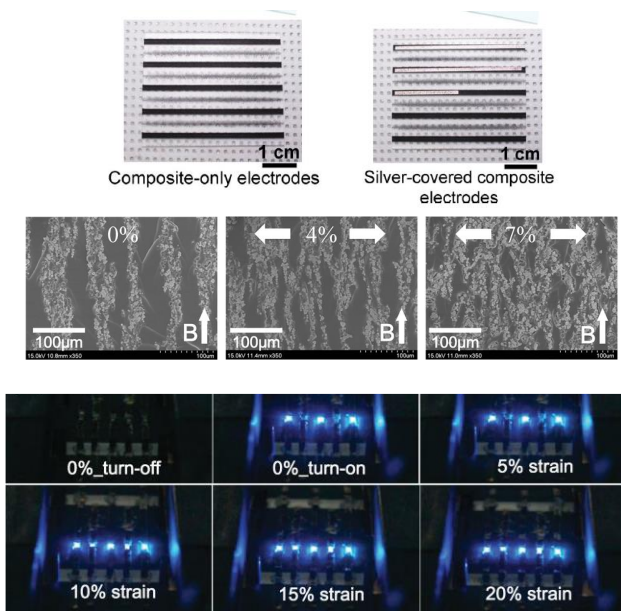
### 2.1. Negatively strain-dependent resistance toward highly stretchable electrodes and stretchable displays with hidden pixels [1]:

When combined with printed silver and composite materials, highly stretchable electrodes can be fabricated as shown in Figure 2. At low stretching state, silver provides electrical conduction. At high stretching state, silver starts to fail in providing electrical conduction, but the composite electrode starts to provide electrical conduction, because the vertically aligned conducting ferromagnetic particles causes negatively strain-dependent resistance. This means that resistance of the composite electrode decreases with tensile strain. The particles are connected to each other, leading to much lower resistance of the silver-covered electrodes with tensile strain. We also properly arranged the composite-only electrodes and silver-covered composite electrodes, so that stretchable display devices with hidden pixels can be demonstrated, where hidden pixels turn on when tensile strain is applied to the array. When array is stretched, the composite-only electrodes starts to provide electric conduction to the hidden pixels which are in off state when the



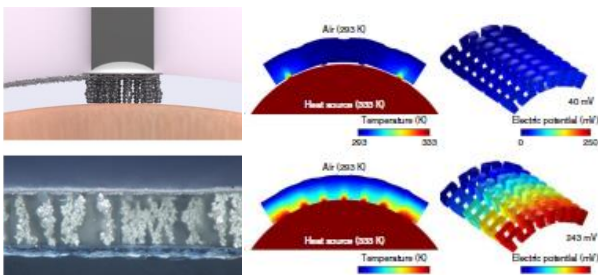
**Figure 1** Composite materials with conducting ferromagnetic particles vertically-aligned by magnetic field, which can be used for vertical electric conduction, localized vertical heat conduction or pressure/temperature sensitive resistors

array is not stretched.



**Figure 2** Composite-only and silver-covered composite electrodes and their usage in stretchable display devices with hidden pixels (adapted from [1])

**2.2. Localized vertical heat conduction [3]:** For body-attachable thermoelectric battery, stretchable substrate such as polydimethylsiloxane (PDMS) must be used. However, such elastomer material is known to be a very poor heat conducting material. Therefore, although highly conformable thermoelectric battery is implemented, body heat is very difficult to transfer to the thermoelectric legs or devices through the substrate having a direct contact with human skin. We successfully demonstrated significant improvement of body heat transfer through the stretchable substrate when properly-patterned vertically-aligned ferromagnetic particles are embedded in the substrate. Since the patterned particles are located right under the rigid legs, they do not degrade stretching or conforming properties of the body-attachable thermoelectric battery system (Figure 3)

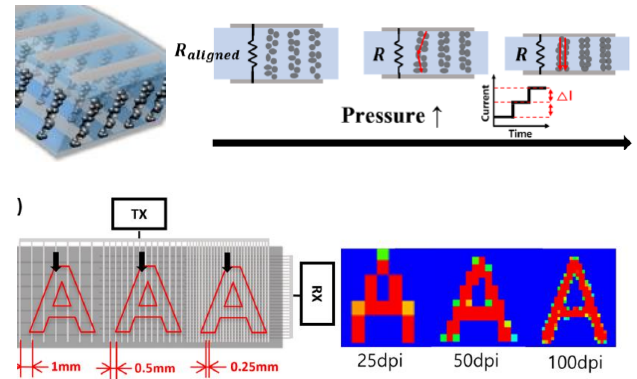


**Figure 3** Localized vertically-aligned ferromagnetic particles in highly conformable thermoelectric battery

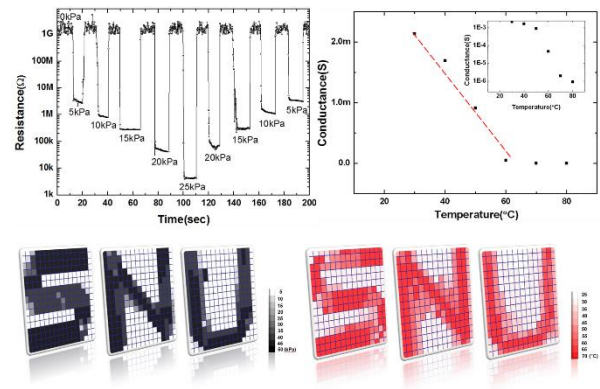
(adapted from [3])

**2.3. Pressure and temperature sensor material [5]:**

Soft pressure and temperature sensors can be used to imitate real human skin, which has various spatial distribution of pressure-sensing receptors. Generally, sensing area and read-out electrodes need to be separately patterned every time corresponding to a specific resolution. Composite with vertically-aligned conducting ferromagnetic particles much reduced such elaborate process for sensor arrays with various resolution. So-called, a universal soft pressure-sensitive platform is developed, where spatial resolution of pressure sensors can be easily tuned. By simply sandwiching the platform between soft electrodes with different pitches, we successfully demonstrated a pressure sensor array with various resolution on a single sensor sheet (Figure 4). If we further optimized array structure by separately patterning sensing area and changing thickness for each pressure or temperature sensing area, we can also fabricate a sensor array where both pressure and temperature can be separately measured (Figure 5). Our soft sensing platform will be a key enabling technology for actually imitating the receptor systems of human skin in robot and biomedical applications.

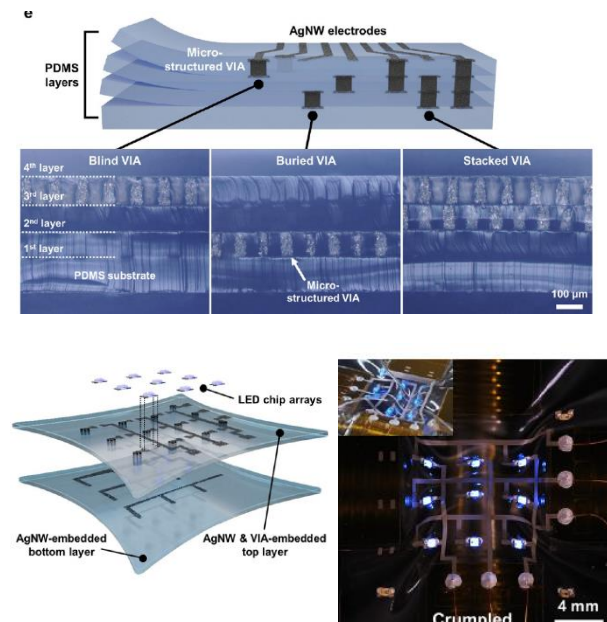


**Figure 4** Non-patterned sheet containing vertically-aligned particles for implementation of pressure sensors with various resolutions up to 100 dpi (adapted from [5])



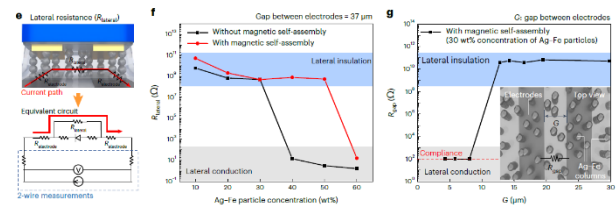
**Figure 5** Integration of pressure and temperature sensors in single platform made of vertically-aligned ferromagnetic particles embedded in an elastomer, where pressure and temperature data can be separately measured.

**2.4. Vertical electrical conduction (Via) [6]:** By further increasing conductivity of the ferromagnetic particles, we can also use the composite in multi-layers stretchable printed circuit board. Silver-coated nickel or silver-coated iron particles can be used in via applications. For sensors, pure nickel or iron particles are used because we need to modulate the resistance range from mega to kilo or kilo to hundreds ohm. However, for via applications, the resistance must be as low as possible and resistance change from external deformation should be minimum. One example is micro-structured via (Figure 5). Instead of using one big via, micro-structured via can effectively reduce any resistance change under various strain ranges. By stacking printed circuit board, multi-layers stretchable printed circuit board can be fabricated.



**Figure 5** Stacked printed circuit board with embedded micro-structured via made of vertically-aligned highly conducting ferromagnetic particles (adapted from [6])

**2.5. Vertical electrical conduction (bonder) [7]:** Bonding rigid components such as LEDs or ICs on stretchable substrates or printed circuit boards is challenging because non-patterned, thick, and rigid bonders easily degrade stretching performance of the whole stretchable electronic systems. If the rigid bonders can be easily located only under the rigid components, they will not degrade the stretching property of the systems. In addition, the rigid bonders can act as rigid islands which effectively engineer strain distribution for rigid and soft area [8][9]. In our site-selective bonder, vertically-aligned ferromagnetic particles provide low contact resistance without electrical crosstalk between fine-pitch pads up to 10 micrometer scales. Our technique will play a key role for integration of multiscale, die-level microdevices on various flexible and stretchable substrates.



**Figure 6** Vertically-aligned silver-coated iron particle provides excellent vertical conduction and lateral insulation up to 10 micrometer scale (adapted from [7])

### 3. Conclusion

In this paper, we reported various usages of composite with vertically-aligned conducting ferromagnetic particles. By using pure or silver-coated ferromagnetic particles, we successfully demonstrated their several key enabling functions essential in various stretchable electronics applications. We believe that if we combined more various ferromagnetic particles with elastomers or adhesives, other novel functions can be added to stretchable displays or soft electronic skins.

### 4. Acknowledgements

This work was supported by the Center for Advanced Soft-Electronics funded by the Ministry of Science, ICT and Future Planning as Global Frontier Project (CASE-2015M3A6A5065309).

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