We focus on **electromicrofluidic (EMF) platform** that integrates MEMS, sensors, actuators, and packaging techniques to explore electrokinetic manipulations, including **electrowetting-on-dielectric (EWOD)** and **dielectrophoresis (DEP)**, of objects **(a)** with broad electric **conductivities**, **(b)** on wide length **scales**, **(c)** in all **phases** of matters, and **(d)** in deformable fluidic **geometries**, for applications of **advanced manufacturing**, **tissue engineering**, **soft robotics**, ***in vitro*** **diagnosis**, **energy harvesting**, and **enhanced heat transfer**.

## 1. ELECTROMICROFLUIDIC (EMF) PLATFORM

### 1a. Electrical Manipulations on Microfluids: EWOD & DEP

Since 2004, Fan-Tasy laboratory have been continuously studying fluidic, thermal, and interfacial phenomena and developing an **electromicrofluidic (EMF) platform** employing two important electrokinetic forces, **electrowetting-on-dielectric (EWOD)** and **dielectrophoresis (DEP)**, to actuate various microfluids sandwiched between parallel plates containing proper electrodes, dielectric and hydrophobic layers. For the simple sandwich structure (substrate/fluids/substrate in **Fig. 1(a)**) without sophisticated microchannels, the EMF platform is easily fabricated, packaged, and operated. On the EMF platform, EWOD electrically modulates the wettability of a solid surface from hydrophobic to hydrophilic and changes the contact angle of aqueous droplets from $\theta_0$ to $\theta(V)$ (Fig. 1(a)); hence EWOD has been widely used for automated droplet actuations in **lab-on-a-chip (LOC)**, **point-of-care (POC),** ***in vitro*** **diagnosis (IVD)**, and optoelectronic devices (prisms, liquid lenses, displays, etc.). Alternatively, DEP drives polarizable particles and dielectric liquids (e.g., oil droplet in Fig. 1(a)) by non-uniform electric fields. By integrating EWOD and DEP, we demonstrate microfluidic functions that break the stereotype and limitations of traditional microfluidics. As shown in **Fig. 1(b)-1(e)**, that EMF offers general electric manipulations of objects: **(b)** with distinct **conductivity** (conductive water and dielectric oil droplets), **(c)** on **cross-scale** (mm droplets and µm particles/cells), **(d)** in **multiphase** (solid, liquid, gas, and plasma), and **(e)** in adjustable **geometry** (discrete droplets and continuous virtual channels).

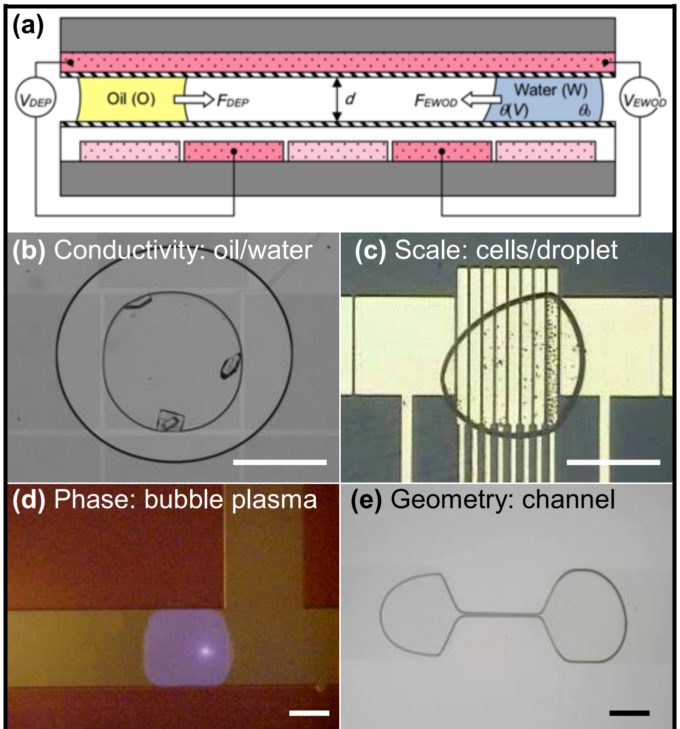


**Figure 1.** Fundamental and general electric manipulations of various objects on an EMF platform. **(a)** Cross section showing fluids sandwiched between two parallel glass plates. **(b)** Driving conductive water and dielectric oil to form a water-core/oil-shell droplet for controllable protein crystallization. **(c)** Actuating cross-scale cells (µm) and droplets (mm). **(c)** Driving air bubbles and plasma. **(d)** Generating a virtual microchannel and pumping between terminal droplets for sample (cell) analysis. Scale bar: 1 mm.

### 1b. Diagnosis Medical Devices and System: automated bioassay & CMOS biosensors

For the facile liquid manipulating ability, EWOD-based medical devices have been developed and commercialized by biomedical companies like Illumina, Oxford Nanopore, GenMark, etc. Collaborating with industrial partners, we develop standard foundry processes of EMF devices and systems (**Fig. 2(a)**), containing MCU, circuits, and GUI, to automatedly perform DNA extraction, DNA amplification, qPCR (real time PCR), dPCR (digital PCR, **Fig. 2(b)**), and immunoassay using commercial bioassay kits. We integrate **semiconductor dies** into the EMF platform, including field effect transistor (FET) biosensors (dashed circles in **Fig. 2(c)**, **2(d)**) and other silicon components (e.g., photodiode, microelectrode array, CMOS image sensors). A custom flip chip packaging process is established to bond an immunoassay-based silicon biosensor (**Fig. 2(d)**) on a flexible printed circuit board (FPC) with a detection window allowing the blood sample to contact the sensor. We aim to provide standard foundry services of the EMF platform based on our IC and MEMS packaging experiences and commercialize related microfluidic products. The flip chip packaging is developed to self-assemble Si dies in crosslinkable building blocks described in the following sessions for 3D/4D soft robots.

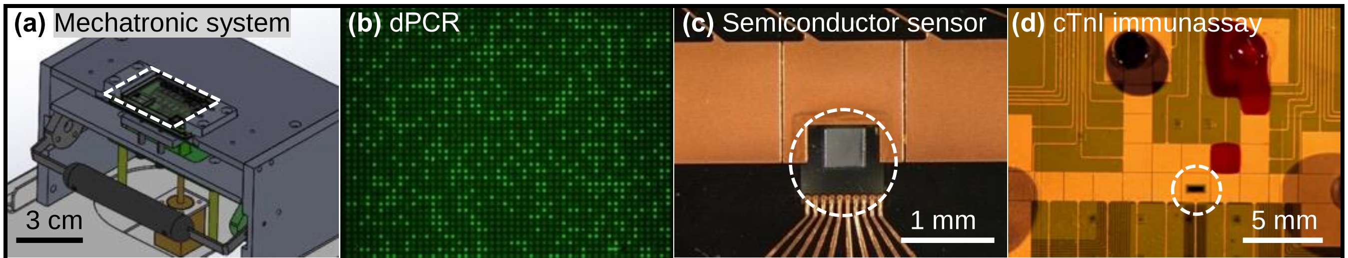


**Figure 2.** Translational EMF cartridges and systems for diagnosis. **(a)** Fabrication and design of EMF devices (dashed region) and mechatronic systems to precisely control the electric signal, magnetic field, temperature, etc. **(b)** Integrated Si or polymer microwell array for dPCR. **(c)** Integrating Si-based dies (dashed region) in EMF devices. **(d)** A Si-based FET biosensor (dashed region) packaged in FPC by flip chip bonding to detect acute myocardial infraction (MI) markers, cTnI.

**2. ADVANCED MANUFACTURING** (videos: http://advances.sciencemag.org/content/2/10/e1600964)

**2a. 3D Planar Architectures: (*Science* http://bit.ly/2eMuUcv; *Nature* https://doi.org/10.1038/nature21491)**

With the general manipulation features, we construct 3D heterogeneous architectures on the EMF platform to provide new tools of **Advanced Manufacturing** for metamaterials or sophisticated and *in-vivo*-like structures recapitulating their physiological functions for healthcare applications, including pharmaceutical screening, pathogen interaction, environmental safety testing, and regulatory studies without using animals. Programmable formation and assembly of building blocks on the EMF platform with EWOD and DEP build 3D architectures. As shown in **Fig. 3(a)-3(d)**, we successfully drive varied objects **(a)** with diverse **conductivities** such as distinct hydrogel prepolymer droplets that are crosslinked or solidified by light (e.g., PEGDA, poly(ethylene glycol) diacrylate or GelMA, gelatin methacryloyl), by chemical reaction (polyacrylamide), or by heat (Matrigel), **(b)** on a wide range of length **scales** from micrometer functional particles or cells to millimeter assembled hydrogel architectures, **(c)** in multiple **phases** including prepolymer liquid droplets and crosslinked solid hydrogel building blocks and **(d)** in adjustable **geometries** to imitate *in vivo* cell microenvironments, to accomplish firm structures (SU8, PDMS) or to offer flexible electronic circuits with a low melting point solidified solder alloy (Cerrolow 117) or a liquid metal (Galinstan).

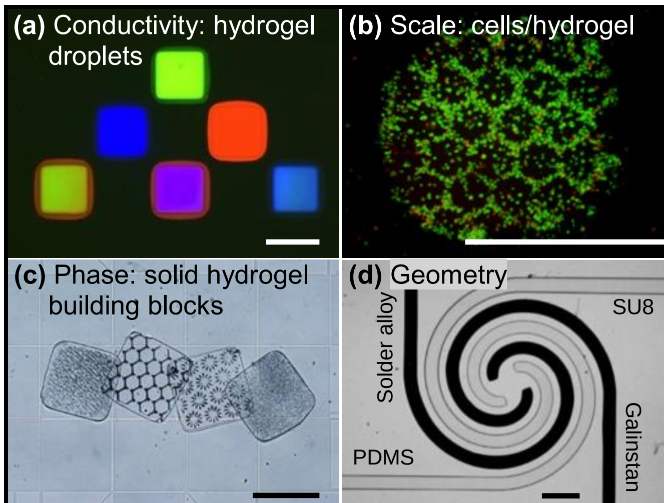


**Figure 3.** General electric manipulations for building block formation and architecture assembly (height 100 μm) on the EMF platform. **(a)** Crosslinkable droplets (PEGDA) with varied conductivities driven to adjust their properties (color) and then solidified to be building blocks. **(b)** GelMA building blocks containing patterned cells (fibroblast NIH/3T3). **(c)** Assembly of solidified PEGDA building blocks. **(d)** Constructing spiral conducting lines with low melting point solder alloy and Galinstan and spiral structures SU8 and PDMS (thickness 40 μm). Scale bar: 1 mm.

3D planar heterogeneous architectures are assembled in liquid phase by combining different crosslinkable prepolymer droplets with particles/cells patterned by DEP (**Fig. 4(a)**). SEM observation in **Fig. 4(b)** shows polystyrene (PS) particle patterns in 5% GelMA after crosslinking and lyophilization. A light pattern, e.g., cross shape in inset of **Fig. 4(c)**, selectively crosslinks the complex prepolymer to obtain a special building block. Engineered *in vitro* liver tissues for **organs-on-a-chip** (**Fig. 4(d)**), containing liver cells (Huh-7, HNF4α-stained, green), endothelial cells (HUVEC, CD31-stained, red), and macrophages (differentiated THP-1) in GelMA, are prepared, co-cultivated for more than 2 weeks. CYP3A4 is induced by rifampicin for toxicity testing of acetaminophen (APAP) at different concentrations with varied designs in 2D/3D configurations. Cells are ready to be patterned in hydrogels on the EMF platform to recapitulate the *in vivo* microenvironments for healthcare applications. In addition, tether-free bio-actuators based on tissues with patterned cardiomyocytes or skeletal muscle cells are investigated as a locomotion force for artificial bio-robots.

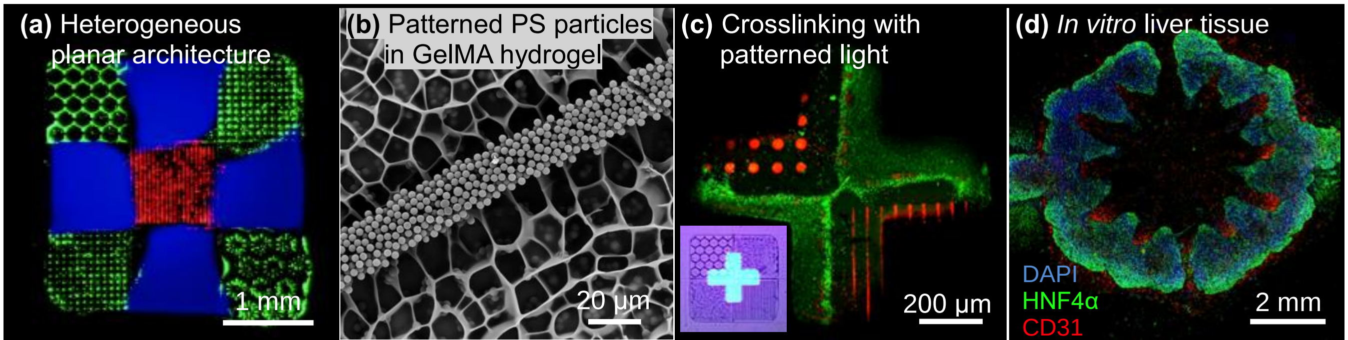


**Figure 4.** Heterogeneous architectures assembly, building block formation, and testing on the EMF platform. **(a)** Contacting 9 PEGDA droplets containing dye (blue) and particles (green and red) for architecture (3 mm × 3 mm × 100 μm) assembly and crosslinking by UV light. **(b)** SEM of 3 μm PS particles patterned by DEP in 5% GelMA hydrogel. **(c)** Building blocks with arbitrary geometries (shown cross-shaped) prepared by partial crosslinking of assembled droplets with adjustable UV light patterns (shown cross in inset). **(d)** Engineered liver tissue containing liver cells (Huh-7, green), blood vessel cells (HUVEC, red), and macrophages (THP-1) is constructed in GelMA (3-10% for stiffness) hydrogels for acetaminophen (APAP) toxicity testing.

**2b. 4D Stereo Heterogeneous Architectures: composite materials with environmental responses**

Time or environmental responsible 4D, curved, or folding architectures are obtainable when a gradient of internal stress, volume shrinkage, or swelling is established. With the EMF platform, appropriate gradient can be generated by gradient crosslinking when grayscale UV light patterns shining on photo-crosslinking hydrogels or elastomers (PDMS) containing photoabsorbers. As shown in **Fig. 5(a)**, an origami PEGDA crane with blue dye and patterned PS particles on the wings is constructed by EMF with a grayscale light pattern. As shown in the inset of Fig. 5(a), the crane can further consist of various hydrogels and functional particles (like Fig. 4(a)) for functional architectures and soft microrobots. Contractile muscle cells, para/ferromagnetic (NdFeB) particles, gold particles, graphene, or other functional particles embedded and reorganized in hydrogels are candidates to actuate the tether-free origami soft microrobots. Other than grayscale light patterns, particles themselves also scatter the incident light and render a crosslinking gradient to bend or curl the architecture (**Fig. 5(b)**) depending on the particle concentration. As shown in **Fig. 5(c)**, hinges with 3 μm red PS particles reorganized by DEP in micropatterns (line/spacing: 30/30 μm) perpendicular to the bending direction are temperature responsive caused by partial crosslinking and PEGDA swelling. Moreover, the proper internal stress and swelling gradient of folding structures can be provided with multilayer structures by stacking hydrogel building blocks (e.g., Fig. 3(c)) or by layer-by-layer crosslinking of unlike hydrogels. For example, PEGDA and GelMA with suitable concentrations, thicknesses, and crosslinking patterns generate dome-shaped, tube-shaped, and other architectures (**Fig. 5(d)**).

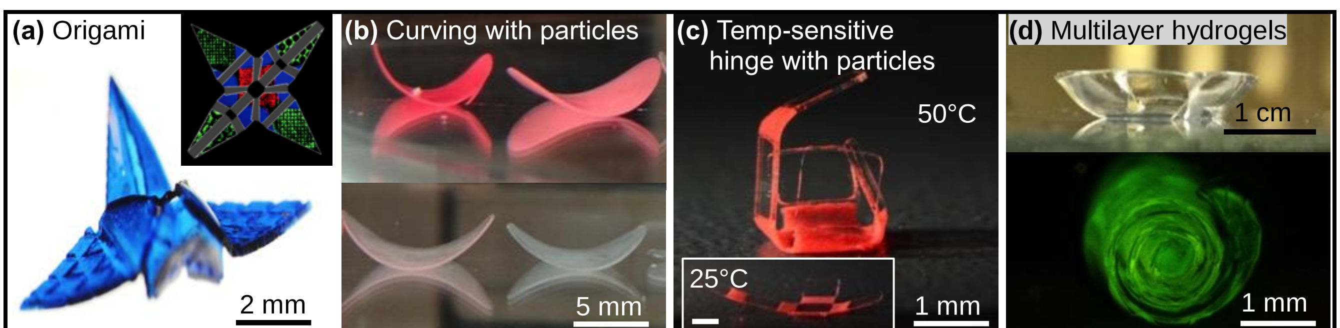


**Figure 5.** 4D stereo heterogeneous architectures with folding or curling structures prepared with photo-crosslinking hydrogels on the EMF platform. **(a)** A PEGDA (thickness 260 μm) origami crane crosslinked with a grayscale light pattern. **(b)** Curled PEGDA (170 μm) with 3 μm red PS particles at concentrations of $5\times10^{9}$-$10^{7}$ particles/ mL. **(c)** DEP organized/patterned 3 μm red PS particles (line/spacing: 30/30 μm) offer temperature sensitive hinge (1 mm × 630 μm × 170 μm) structures. **(d)** Laminating multiple hydrogels, PEGDA and GelMA, with proper concentrations, thicknesses, and crosslinking patterns to obtain proper local curvature and final architectures.

## 3. ENERGY AND HEAT TRANSFER

### 3a. Enhanced Heat Transfer with Active Surfaces

Our surface wettability modulation and liquid manipulation abilities are ideal for enhanced heat transfer, especially for phase change heat transfer when the appropriate wettability of the solid surface is pivotal to nucleation, growth, and detachment of the discrete phase, i.e., bubbles in boiling and droplets in condensation. Surface wettability can be adjusted with micro and nano-structures as shown in **Fig. 6(a)**. Employing EWOD, the adjustable wettability further improves heat transfer in varied stages of phase change heat transfer that usually require opposite wettability. For example, condensation (**Fig. 6(b)**) prefers hydrophilic surfaces in nucleation but droplet detachment is favorable on hydrophobic surfaces. EWOD controls the surface wettability and actively pumps away the droplets with a desirable volume range determined by the EWOD electrode size and applied voltage. Furthermore, EWOD improves wicking in heat pipes and suppresses the Leidenfrost state of film boiling. Droplets of coolants, ionic liquids, and liquid metals driven by EMF also offer on-demand electronics cooling.

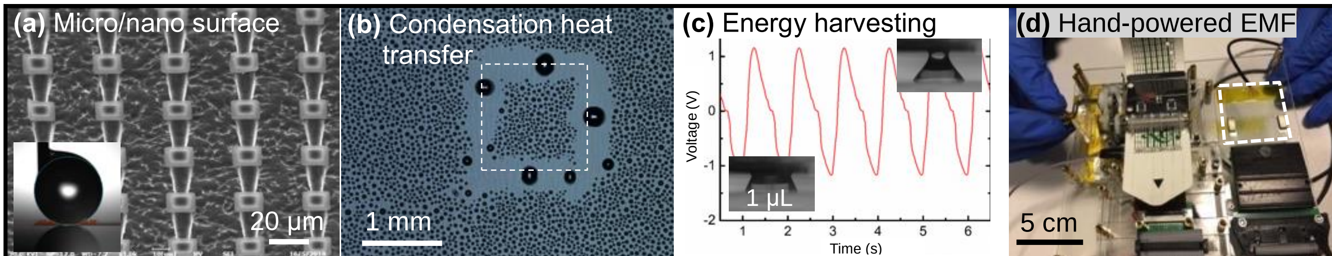


**Figure 6.** Energy applications of EMF. **(a)** Micro and nano-structured hydrophobic surface. **(b)** Controllable coalescence and pumping of condensed droplets by EWOD (one electrode indicated by a dashed square). **(c)** Periodic droplet deformation between electrodes for electric charge generation and energy harvesting. **(d)** Battery-less and PC-less system with a modified hand-cranked music box, a triboelectric generator, and a paper strip with pre-punched holes to perform bioassays on the EMF device (dashed region).

### 3b. Energy Harvesting: nanogenerators

By reversing the EMF droplet manipulation processes, the natural and low-frequency movements of fluids (e.g., 1 μL droplet in **Fig. 6(c)**) caused by human motion, rainfall, or ocean wave can be harnessed with compact and wearable nanogenerators by reversed EWOD, piezoelectric, triboelectric, or electromagnetic mechanism, for powering distributed Internet of Thing (IoT) or implanted medical electronics. We investigate various microfluidic energy harvesting techniques based on the modulation of electric double layer (EDL) charge at the liquid/solid interface, including using magnetic fields and ferrofluids. A battery-less EMF system (**Fig. 6(d)**) with a modified hand-cranked music box is developed; crank motion periodically contacts and detaches metal and polytetrafluoroethylene (PTFE) polymer surfaces to generate power with the triboelectric effect; droplet functions are pre-programmed on a paper strip with punched holes without a PC or other electric circuits and controllers. The hand-powered systems are deployable and useful in resource-limited regions for rapid diagnosis.

### 3c. Renewable Energy Opportunities

With proper optical properties, the EMF-driven fluids interact with the incident light and provide various **optofluidic** functions. For example, an array of optofluidic prisms modulating light by EWOD can track, steer, and concentrate the incident solar beam to an energy collector or to be used for indoor lighting. With the ability to assemble and align $TiO_2$ particles, the efficiency of a dye-sensitized solar cell (DSSC) can be improved with direct electrons conduction and ion diffusion paths and high incident light. Our experiences also contribute to implement related energy devices, such as proton exchange membrane fuel cells (PEMFC). The diagnosis functions of EMF can be applied to screen and select algae, bacteria, and other organisms for biofuel.

### 3d. New (Meta)materials for Energy

3D and 4D functional composite and heterogeneous materials prepared by EMF advanced manufacturing technique allow us to tune their properties of heat transfer, energy conversion, and energy storage. Metamaterials composed of varied continuous and discrete materials, such as phase change materials, aerogels, electrocaloric materials, would render ideal electromagnetic and/or thermal properties in energy applications.