Micro Crumples for Self-Assembly of Field Emission Devices

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ABSTRACT

When foils are crumpled they create sharp features that provide a reaction to the applied force. In this paper we consider the possibility of using the sharp features in conducting crumpled foils for use as field emission devices. This would be of interest for self assembled, low cost, large area field emission displays on flexible substrates. In this paper, we identify the geometry of the structures arising in a crumple and model its vertical electric field. Then we investigate some techniques of manufacturing thin film crumples on flexible substrates.

Keywords: field emission devices, self assembly, displays, crumples

1 INTRODUCTION

Crumpling is ubiquitous in nature and is observed across various length scales from molecules to folding land masses creating mountains. The mechanics and geometry of a crumpled sheet can provide insights into re-engineering conventional designs, e.g. the front end of vehicles for safety, light and strong structures, and tailoring clothes to fit better. Simply put, crumpling is a form of packing. Foils crumple due to a combination of bending and stretching, with more bending than stretching [1]. The mechanical properties of a crumple influence its geometry and vice versa. When a foil is crumpled, the energy is not distributed across the foil uniformly, but is focused at vertices and ridges. These focus points can be thought of as compressed springs providing the reaction to the applied force. When the applied force is removed, the features that retain their elasticity spring back, allowing the foil to relax. This release of stored energy is responsible for the crackle of a freely expanding plastic crumple.

The focus points in a crumple lead to the formation of sharp features. When a conducting crumpled foil with sharp features is charged, the charge distributes itself non-uniformly so as to keep the surface at the same potential. Points of high curvature have a higher charge density and subsequently a higher vertical electric field. The charge density for quartic surfaces is shown to be proportional to the fourth root of the Gaussian curvature [2], while that for quadric surfaces is almost directly proportional to the local curvature.

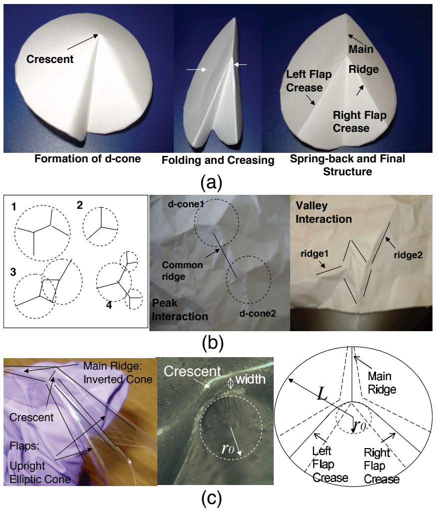


Figure 1: (a)A d-cone is formed by forcing a circular sheet of radius r through a cylinder with radius $< r$ via a point-force applied at its center. Crumples cause d-cones to fold and crease, and then spring back when the applied force is removed. (b) Crumpled foils have various features which involve d-cone interactions - peaks (label 1), isolated d-cones (label 2), valleys (label 3) and networks (label 4) are some common features. (c) Micrograph of the crescent at the top of the d-cone formed of a plastic sheet. In the crescent energy minimisation defines $r_0 \propto L^{2/3}$.

In this paper we attempt to develop a field emission device using the sharp features of a crumple. In the next section we study the geometry of a crumple. Then we model the vertical electric field of a conducting crumpled foil. Subsequently, we study some techniques of manufacturing thin film crumples on flexible substrates. The inspiration for this work is the self assembly of low cost field emission displays on flexible substrates.

2 GEOMETRY OF CRUMPLES

The basic geometrical entity in a crumple is the developable cone (d-cone) [3],[4]. A d-cone can be built by taking a circular foil of radius L and forcing its face into a cylinder of smaller radius via a point force applied at its center. The surface area of the foil is conserved in the confinement by taking the shape of a d-cone (Figure 1a). Strong crumpling forces cause folding and creasing (Figure 1a) creating the main ridge, and left and right flap creases with the top being a sharp crescent. If the folding goes beyond the elastic limits, the structure remains crumpled even after the removal of the applied force while for less intense folds, the d-cone springs back. Figure 1b shows some common features (labeled from 1 to 4) seen on a crumpled foil. One sees not only single d-cones (labeled 2) but also a network of interacting d-cones (labeled 4) forming ridges. Peak formations (labeled 1) occur if the crumpling force causes a creased two folded d-cone. Valley formations (labeled 3) appear when local elastic shells in the middle of the foil are deformed [5]. The features of a crescent boundary of a d-cone formed using a plastic sheet is shown in Fig 1c. The upper part of the main ridge appears like an inverted cone with the crescent as its base since it is energetically cheaper to bend the main ridge far away from crescent. The creased left and right flaps appear like upright elliptic cones. The flap cones, unlike the main ridge cone, are wider at the bottom since any folding force results in the flaps moving towards each other without much creasing and at the expense of creasing the main ridge. The top of flaps and the base of the main ridge cone define the width and radius r_0 of the crescent, respectively. The minimisation of the bending and stretching energies of the main ridge near the crescent top define $r_0 \propto \omega^{1/3}L^{2/3}$, where ω is the thickness of the foil [6]-[9]. Since the bending stiffness and elastic modulus are functions of the foil thickness, the thickness strongly determines the curvature of the creases so that crumples on thinner foils have sharper features.

3 ESTIMATION OF ELECTRIC FIELD

Consider a conducting crumpled foil, spread out and laid on the plane $z = 0$, while the electric field is to be estimated in the plane $z = d$. If feature height is h, we can divide them into two categories - d-cones of height $\approx h$ (of the order of d) and small features of height $<< h$. Ridges, though prominent, arise from d-cone interactions. For small features the vertical electric field is equivalent to that due to a sheet charge. The d-cones generated by light crumples generate a vertical electric field similar to a uniformly charged regular cone. However, the flaps of a d-cone can be modeled more generically as elliptic cones as described earlier. This model is tested against COMSOL [10] based simulations shown in Figure 2. A geometry similar to a crumple was chiseled out of conic sections for simulations where the foil was placed in a medium with dielectric coefficient 4.2 and provided a potential of 100V. Figure 2a illustrates the electric field in the plane $z = d = 2mm$ while Figure 2b compares the vertical electric field at $(0, 0, d)$ for varying d. Note that the point $(0, 0, h)$ is above the surface of the d-cone and hence the field is non zero. The model corroborates with simulations and scales for any arbitrary unit of distance, after allowing for sources of error in geometric differences. In a random crumpled foil, the statistics of the ridge lengths, orientations and curvature is required for the vertical electric field at any point. It is however useful to develop a scaling law for the vertical electric field due to a single d-cone formed of a circular conducting foil of radius L and thickness ω. It can be shown that the vertical electric field of this d-cone would be $\propto (L/\omega)^{1/\gamma}$ where $\gamma \approx 3$.

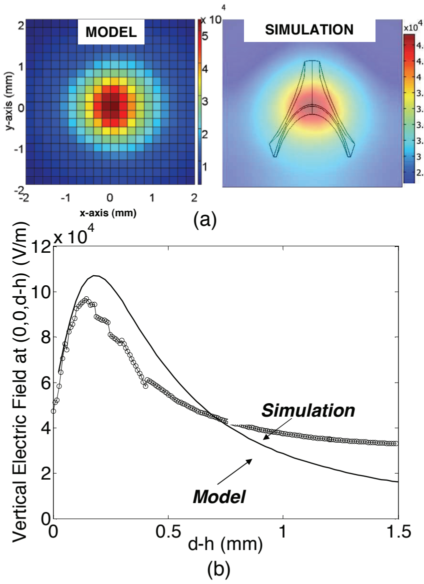


Figure 2: Comparison of model with COMSOL simulations on a conducting crumple with $h = 1.4mm$. (a)Comparison of vertical electric field distribution in the plane $z = 2mm$ and simulation. The dimensions of the plane are comparable and the maximum field is $\approx 45kV/m$. (b)Comparison of the vertical electric field at $(0, 0, d - h)$ for varying $d - h$. Note that the point $(0, 0, h)$ is above the surface of the d-cone and hence the field is non zero

4 FABRICATION OF FIELD EMISSION DEVICES

Conventionally field emission devices are fabricated as Spindt tips [11] using Molybdenum or using forests of carbon nanotubes [12]. In order to fabricate low cost field emission devices based on thin film crumples over flexible substrates, we must restrict ourselves to several constraints. Firstly, the conducting foil must be able to withstand mechanical stresses without breaking or

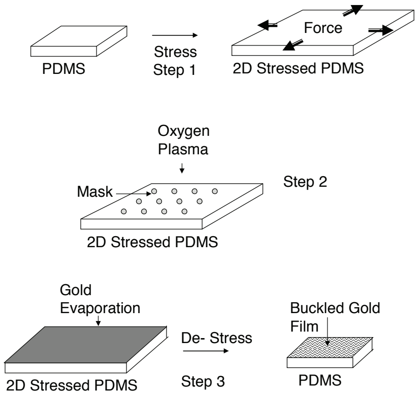
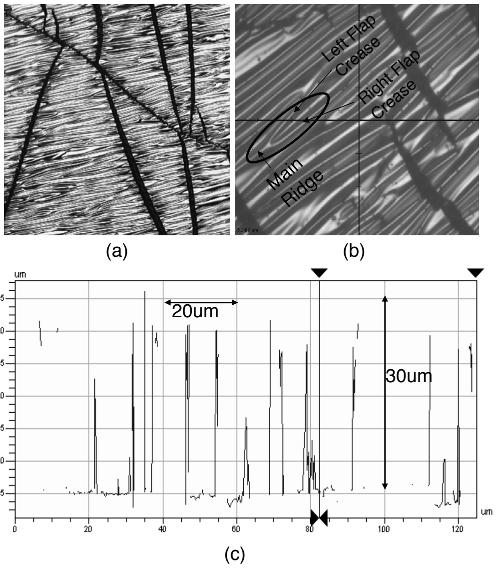


Figure 3: Process flow for the self assembly of crumpled field emission devices

cracking due to it being on a flexible substrate. Due to this we constrain ourselves to malleable metals such as gold and aluminum. Secondly, the metal to be used for field emission must have a low work function in order to enable electron emission at lower voltages. Thirdly, flexible substrates are generally based on organic polymers. Not all polymers remain chemically and/or mechanically stable while undergoing fabrication processes required for conventional inorganic electronics. Thus, the process flow must be bound by this constraint.

4.1 Process flow

We consider a fabrication process in which poly-di methly silicoxane (PDMS) is used as the substrate and gold film is the material of choice for the electrode, in spite of its higher work function than aluminum, due to its superior mechanical properties and chemical inertness. The key element of the process flows is self assembly of crumples by the mechanical buckling of the metal film using techniques similar to those presented elsewhere [13]. The process flow is shown in Figure 3. First PDMS is prepared using the commercially available Sylgard 184 silicon elastomer preparation kit. Simultaneously, a silicon wafer with an optically smooth silicon oxide surface is coated with a monolayer of trichloro (1H,1H,2H,2H-perfluorooctyl) silane which makes the surface extremely hydrophobic due to the fluorine termination. The prepared PDMS is then uniformly spun coat on the hydrophobic surface of the silicon wafer and left to cure at 60C for 4 hours. The cured PDMS is then easily peeled off the surface of the wafer and stretched and pinned in 2 dimensions over a clean glass slide as shown in Step 1 of Figure 3. Then, the stretched PDMS is exposed to oxygen plasma through a mask of micropores as shown in Step 2. This exposure allows the exposed spots of the PDMS to increase in surface energy thereby becoming sticky. Subsequently, gold is evaporated onto the treated PDMS film to enable the formation of a 50nm gold film. This film is pinned to the PDMS in the micro-spots exposed to oxygen plasma. Finally, the PDMS is de stressed and returned to its original shape. The gold film now buckles in 2 dimensions. If the film were to be thin enough, the film would buckle in the regions where it remains unpinned to the PDMS substrate in order to pack itself into the smaller surface area thereby creating crumples with periodic d-cones.



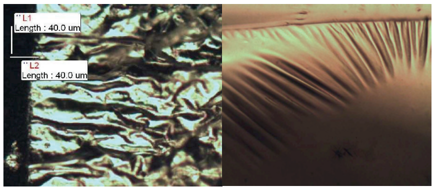
(a) (b) (c)

Figure 4: (a) Buckled gold film (50nm thick). (b) Zoom in of (a) showing stretched d-cones due to unequal stress between the 2 dimensions. (c) Profile scan of the surface shows d-cones to be about 25um tall an 1um to 5um wide.

The crumpled surface is shown in Figure 4a. The 2 dimensional stresses being unequal has created d-cones stretched in one dimension along with cracks in the film to relieve stress. A zoom in of the features is shown in Figure 4b, where the main ridge and right and left flaps of the d-cones are visible clearly. A profilometer scan of the surface is shown in Figure 4c. Typical features of the d-cones define them to be about 25um in height and 1um to 5um wide.

4.2 Other fabrication methods

While the above method of fabrication shows a successful creation of periodic d-cone assembly, other methods may be used to self-assemble crumples. For example, fabrication of conducting micro-crumples can be done by depositing a metallic film over a heat shrink organic layer. In Figure 5a, silver film was deposited on thin film of paraffin which was then heated to 60C. The thermal stress in the paraffin makes it buckle and



(a) (b)

Figure 5: Alternative means to self assemble crumples (a) Buckled silver film on paraffin. (b) Buckled silver film on PVP

contract leading to crumpling in the silver film. The disadvantage of this process is that the deforming paraffin causes the crumple formation to be random and it is not known where the d-cone tips lie. However, this disadvantage is moot since statistically the number of tips over a large enough area (much greater than 2500umsq - the feature size width squared) would be the same. However, a prominent disadvantage is that the deforming paraffin also causes deformations in its height thereby making the substrate uneven. This varies the height profile of the crumple formation significantly.

In order to overcome these difficulties other heat shrink polymers can be used. In Figure 5b, silver film was deposited on square shaped poly-4-vinylphenol (PVP) films. PVP cross-links upon heating leading to wrinkling of the silver film near the vertices of the square. The advantage of this method is that the position of the crumples are well defined.

5 CONCLUSION

In this paper we investigated the novel idea of using the sharp features of crumples to self assemble field emission tips by crumpling conducting films. The application targeted was the self assembly of field emission displays on flexible substrates. We studied the geometry of crumples, and modeled the vertical electric field to be expected by such a geometry. Significantly, a scaling law for the vertical electric field was proposed. The scaling law defined the vertical electric field to be proportional to $(L/\omega)^{1/3}$ with L being the radius of a circular sheet on which a single crumple feature (d-cone) is formed and ω being the sheet thickness. The paper then investigated a means to create periodic crumple features through the 2 dimensional buckling of gold films on PDMS. This lead to periodic crumples of 25um height and about 1um to 5um width. The paper introduces many avenues for future work. For example, what is the exact model for the field emission current due to a d-cone, how can one improve uniformity in the crumple fabrication etc.

In summary this paper introduces a new idea to self assemble field emission displays on flexible substrates.

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