Flexible Wavy Structures for Inorganic Electronic Materials

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I. Abstract

In order to apply inorganic materials with high carrier mobilities to flexible electronics, wave-like ribbons of Si and GaAs deposited on plastic substrates were fabricated and tested. Inorganic electronic films are brittle and generally fracture at 1~2% of strain. Yet, a device with the wavy structure can buckle, or change its wavelength and amplitude, to accommodate stretching, compressing, and bending. Thus, buckling allows the device to experience significant deformation without causing fracture in the inorganic films themselves. Wavy ribbons could be stretched and compressed by up to 60% and 30%, respectively, much greater than the 12% limit reported for an inorganic electronic device with stretchable island interconnects. Also, wavy ribbons were bent to radii of curvature below 6 mm, nearly matching those of prototype flexible organic electronic devices. Wavy inorganic semiconductor devices showed consistent electrical performance even when they were deformed by 5~15%. Moreover, these devices performed consistently when they were subjected to repeated cycles of deformation. However, further investigation is necessary to develop more complicated devices that tolerate even greater deformation and minimize mismatch strains between their components.

II. Introduction

1. State of the art / Broader impact of proposed work

Several research groups have produced flexible high-performance electronic devices composed of metals and inorganic semiconductors deposited on polymer substrates [1, 2, 3]. For instance, a GaAs field effect transistor on a flexible poly(ethylene terephthalate) substrate can operate at a very high frequency above 1 GHz while attaining a radius of curvature of 14 mm [1]. Also, a stretchable electrical interconnect composed of rigid islands connected by gold films on a polydimethylsiloxane (PDMS) substrate can tolerate up to 12% strain [2]. However, commercial prototypes of flexible electronics, capable of being bent to a radius of curvature of 3 mm, are composed of organic materials, primarily pentacene [4]. Nevertheless, inorganic electronic materials have more potential to constitute high-performance devices since their charge carrier mobilities are two to six orders of magnitude greater than those of the organic counterparts [5]. Moreover, inorganic materials also bypass the vulnerability to moisture suffered by organic electronic materials whose moisture exposure limit is $10^{-6} \sim 10^{-1}$ g/m^2/day of water for a device lifetime of one year [6]. With their superior carrier mobilities and robustness, flexible inorganic electronic materials may constitute a new generation of high-performance, mobile, versatile, and rugged electronics. Some possible applications are radio identifier tags, wearable electronic devices, and mobile and foldable computers with paper-like displays.

2. Definition of material challenges to be overcome

Flexible portable electronics require their conducting and semiconducting components to be in the form of thin films. These inorganic thin films typically fracture at about 1~2% strain, which is an order of magnitude smaller than that of bulk metals [1, 7, 8, 9]. A single neck forms in a metal thin film very quickly and leads to rupture before the entire film can stretch beyond a strain of 1~2%, due to the film's small thickness to length ratio [8]. Inorganic semiconductors are inherently brittle, and the cracking of silicon wafers has been a major problem in the production of integrated circuits [10]. To further complicate the challenge, strain from built-in stresses may cause misalignment between different parts of a device and deteriorate the device's electrical performance [8]. Although the island interconnect structure can tolerate strains as high as 12% [2], it is suitable only for low density electronic devices [11]. Furthermore, for more extreme deformation, it is necessary to establish inorganic electronic material structures that can tolerate strains above 20% while maintaining conductivity.

3. Hypothesis or rational to meet challenges

Semiconductor or metal ribbons arranged in periodic, wave-like geometries can accommodate large strains by buckling, or by changing their wavelengths and amplitudes. The brittle inorganic materials themselves do not experience localized necking even at strains much greater than the intrinsic 1% limit because the entire structure – the plastic substrate plus wave-like ribbons – accommodate strains [11]. Such a structure can be fabricated by depositing semiconductor or metal strips on a pre-strained plastic substrate, such as PDMS; releasing the pre-strain then results in a spontaneous formation of a wave-like structure, which can tolerate up to about 15% strain [11]. To further increase the strain limit, the wavelengths and amplitudes of the ribbons can be optimized by lithographically pattering the adhesion sites of the inorganic ribbons on the plastic substrate [12]. Using the optimal wave-like geometries, the strain limit can be increased up to 100% even for such brittle materials as Si and GaAs [12]. This wavy ribbon structure can avoid fracture at high strains and therefore allow high-performance inorganic electronic devices to continue functioning properly even under severe deformation.

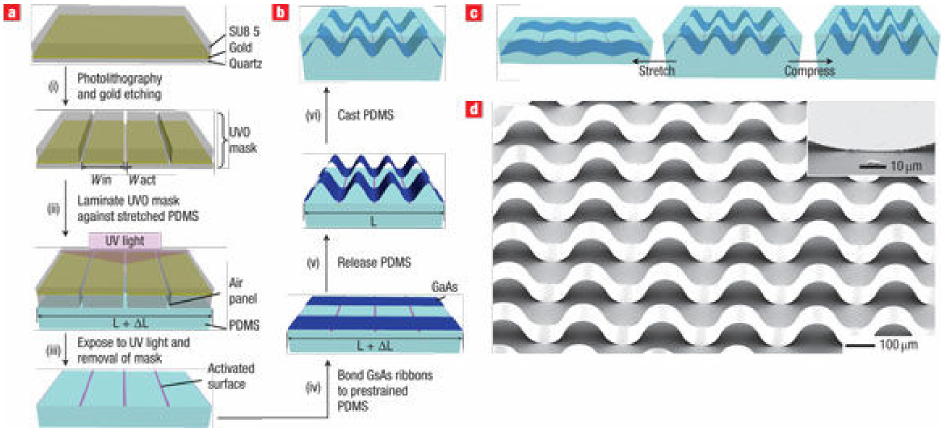

Figure 1. Fabrication process (a, b), mechanical schematics (c), and scanning electron micrographs (d) of buckled GaAs ribbons [12]

III. Experimental

Rogers et al. investigated the mechanical and electrical responses of wavy buckled GaAs and Si ribbons, about 100 μm wide, while their PDMS substrates were stretched and compressed by mechanical stages [11-14]. The end-to-end lengths of the ribbons on their PDMS substrates were measured from optical micrographs. Then, the "stretchability" or "compressibility" of each buckled structure was calculated by the formula, $(L'-L^0)*100\%/L^0$, where L^0 is the equilibrium ribbon length and L' is the ribbon length at fracture. The stretchabilities and compressibilities of wavy structures with different initial wave lengths (100 μm, 200 μm, 300 μm, and 400 μm) were measured at fracture, while the pre-strain and adhesion site size were kept constant at 60% and 10 μm, respectively [12]. Buckled GaAs ribbons on PDMS were also deformed concave up and down to investigate their bendability [12]. Current and voltage were measured across field effect transistors composed of wavy buckled Si [11] and GaAs [13] ribbons while they were stretched and compressed (by 9.9% for the Si device and 4.7% for GaAs). Furthermore, wavy pn-diodes were subjected to 100 cycles of compressing (~5%), stretching (~15%), and releasing while their current-versus-voltage measurements were taken [14].

IV. Discussion

The mechanical testing of buckled semiconductor ribbons on PDMS displayed excellent flexibility [12]. While the ribbons with an initial wavelength of 100 μm cracked immediately upon the release of the pre-strain (shown in Figure 2) as the strain limit of GaAs was exceeded, those with an initial wavelength of 400 μm exhibited the best stretchability and compressibility – up to 60% and 30%, respectively. From this result, it was deduced that buckled ribbons with larger ratios of initial wavelength to adhesion site size would allow greater deformation, as pre-strains larger than 100% could possibly be achieved to permit even more buckling of the waves. In the bend tests, the wavy GaAs structures attained a radius of curvature of 5.7 mm, approaching the bendability of organic electronics (radii of curvature 3~5 mm) [4]. Optical micrographs showed that the wavy profile changed to accommodate stretching, compressing, and bending.

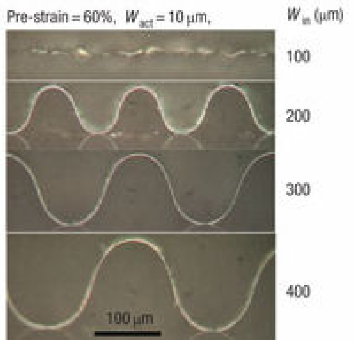

Figure 2. Comparison of profiles of buckled GaAs ribbons with different initial wavelengths [12]

Wavy semiconductors maintained consistent electrical performance at strains within the range of 5%~15%. There were no systematic variations in the current-versus-voltage characteristics of the deformed Si [11] and GaAs [13] transistors. The reversibility of electrical performance under repeated stretching and bending was also confirmed because, again, no systematic variations in current-voltage profiles were observed, as indicated in Figure 3 [11]. In fact, in these electrical tests, the differences between deformed and non-deformed devices were so minute that they were attributed to minor discrepancies in the quality of probes [11]. At higher strains (~40%), however, a decrease in current was observed due to defect formation in the lattice of the semiconductor ribbon [12].

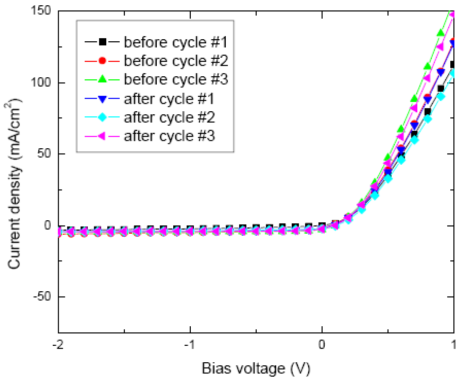

Figure 3. Electrical measurements of wavy pn diodes before and after ~100 cycles of stretching/compressing [14]

V. Conclusion

There is an ongoing effort to construct high-performance electronic devices that could be stretched, compressed, and bent into various forms. Wavy buckled structures composed of Si and GaAs ribbons withstood unprecedented degrees of deformation in thin inorganic semiconductor films and maintained their electrical properties at moderate deformation. Similar wavy structures may be constructed out of other materials -- metals and other semiconductor materials, including GaN and InP -- as well as different nanoscale structures such as nanomembranes and nanowires [12]. The strain and curvature limits can be increased by using plastic substrates even more deformable than PDMS and by developing more precise and nanoscale adhesion site patterning techniques, such "stamping" charge patterns on substrates [15]. Also, to maintain uniform electrical properties at strains higher than 15%, a method to suppress lattice defect formation must be investigated. Furthermore, more complex electronic devices must be constructed from these wavy inorganic materials while taking into account the mismatch problem between different layers [9]. Although these challenges are daunting, inorganic materials have great potential to become more attractive candidates for flexible electronics than organic materials.

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