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Stretchable silicon electronics and their integration with rubber, plastic, paper, vinyl, leather and fabric substrates

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ABSTRACT

Electronic systems that offer elastic mechanical responses to high strain deformations are of growing interest, due to their ability to enable new electrical, optical and biomedical devices and other applications whose requirements are impossible to satisfy with conventional wafer-based technologies or even with those that offer simple bendability. This paper describes materials and mechanical design strategies for classes of electronic circuits that offer extremely high flexibility and stretchability over large area, enabling them to accommodate even demanding deformation modes, such as twisting and linear stretching to 'rubber-band' levels of strain over 100%. The use of printed single crystalline silicon nanomaterials for the semiconductor provides performance in flexible and stretchable complementary metal-oxide-semiconductor (CMOS) integrated circuits approaching that of conventional devices with comparable feature sizes formed on silicon wafers. Comprehensive theoretical studies of the mechanics reveal the way in which the structural designs enable these extreme mechanical properties without fracturing the intrinsically brittle active materials or even inducing significant changes in their electrical properties. The results, as demonstrated through electrical measurements of arrays of transistors, CMOS inverters, ring oscillators and differential amplifiers, suggest a valuable route to high performance stretchable electronics that can be integrated with nearly arbitrary substrates. We show examples ranging from plastic and rubber, to vinyl, leather and paper, with capability for large area coverage.

INTRODUCTION

Stretchable electronics on plastic sheets, metal foils, rubber slabs and other unusual substrates is an important technology for its potential role in various important future applications, such as smart fabrics, wearable biomedical monitoring systems and portable, lightweight information systems [1-8]. If clothes with smart fabrics can monitor the condition of a patient, then point of care monitoring could be realized and patients could be diagnosed even outside of the hospital. To achieve electronic systems on rugged surfaces, such as fabric or

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cloth, high performance stretchable electronics is essential. Such electronics cannot be built with conventional wafer based systems or with simple bendable electronic devices on plastic films. The challenge is that electronic devices embedded on the surface of clothing can be bent or even folded whenever the patient moves. Such folding or extreme bending can cause large levels of strain in the device. Even flexible electronic devices on plastic film may fail in such cases. Some organic transistors may be compatible with mild bending, but their poor electrical performance in comparison with the single crystal silicon devices frustrates high performance electronic system applications.

Recently, single crystal silicon stretchable circuits with non-coplanar and deformable serpentine bridges were reported [9]. Here we demonstrate that these stretchable circuits can be integrated on fabric, paper, vinyl and leather, with ability to function properly after folding and extreme deformations. The left image of Fig 1 shows an image of a folded single crystal silicon based CMOS inverters on a thin PDMS sheet. The folded edge can be magnified through scanning electron microscope (SEM) imaging to show that the non-coplanar serpentine bridges of the inverter are stretched, thereby preventing the strain from appearing at the location of the active device to eliminate mechanical failures. The stretched interconnects are clearly visible by comparing inverters at the folded corner (right top SEM image) and those at the side (right bottom SEM image). This general structure enables CMOS circuits to be integrated on various surfaces.

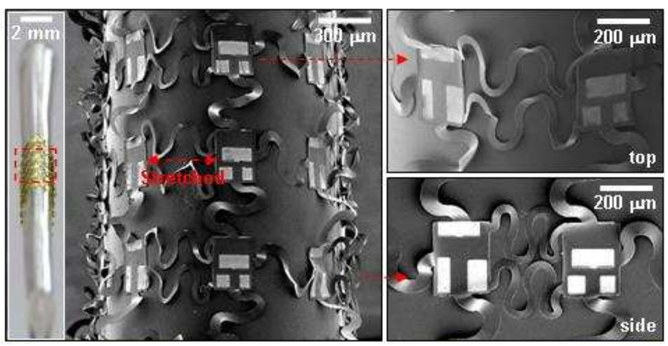

Figure1: Scanning electron microscope (SEM) image for folded edge (left), magnified SEM view at the folded edge (right top) and side (right bottom); inset shows the large-view optical image of folded inverters. Adapted from ref. [20]

EXPERIMENT

The fabrication process for ultrathin CMOS circuits is similar to that in previous reports. [9] After forming devices on a carrier wafer (Fig 2A), releasing the ultrathin circuits by removing an underlying layer of poly(methylmethacrylate) (PMMA, MicroChem, USA), picking them up with a polydimethylsiloxane (PDMS, Dow Corning, USA) stamp, depositing Cr/SiO_2 (3nm/30nm) selectively on the backsides of the active device islands through a shadow mask and transfer printing onto surfaces coated with PDMS results in stretchable CMOS circuits on various surfaces (Fig 2B). The materials can include fabric, vinyl, leather or paper and the structural formats can be either flat or in curved, balloon-like or related shapes. An important aspect of this transfer printing and bonding process is that it prevents the detachment of ultrathin circuits during repetitive deformations, while allowing the non-coplanar deformable bridges to move without restriction out of the plane of the substrate. This outcome is achieved using selectively deposited SiO_2 on the backside of active islands to form strong covalent bonding to

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the PDMS surface. To enhance this chemistry, the PDMS surface can be activated with -Si-OH groups formed by treatment with ozone. On the backsides of the serpentine bridges, on the other hand, only weak Van der Waals (VdW) interactions with the PDMS are present. As a result, upon stretching, these bridges can delaminate to move out of the plane, as shown in the right scanning electron microscope (SEM) image of Fig 1.

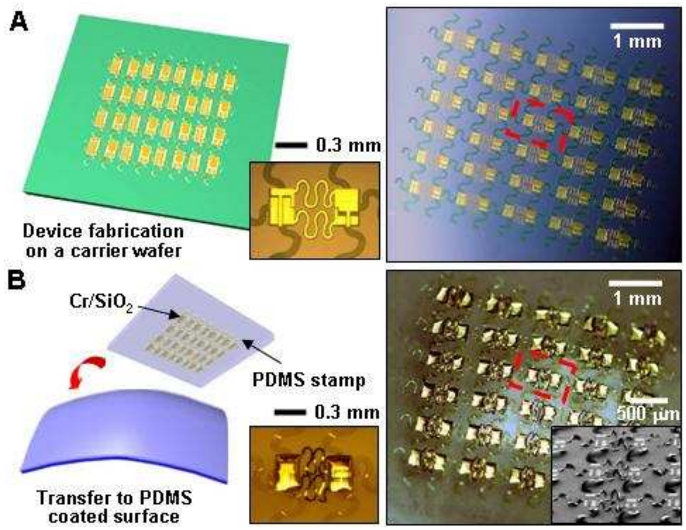

Figure 2: (A) Schematic illustration of fabricated devices on a carrier wafer (left) and its image (right); inset at the center shows a microscope image of a stretchable CMOS inverter (red dotted box on right frame). (B) Schematic illustration for transfer printing of ultrathin CMOS circuits after selective deposition of SiO_2 (left) and their image after transfer printing (right); inset at the center shows a microscope image of a transferred stretchable CMOS inverter (red dotted box on right frame). Adapted from ref. [20]

RESULTS and DISCUSSION

In product level applications, such as wearable electronic systems, extreme bending or folding can occur. Under such conditions, non-coplanar bridges can stretched at locations of the fold to prevent mechanical failures. As an example, the top and left frames of Fig 3 show an image of a bent system and a schematic diagram of deformed CMOS inverters on fabric. In the inset, a magnified view of CMOS inverters on fabric is shown. Electronics embedded on/into fabric are of widespread interest [12]. Simple electronic texiles can consist of metal or other conducting material threads or fibers coated with conducting polymers, for use as flexible antennas [13]. Integration of conducing textiles with active components, such as organic field effect transistors or organic electrochemical transistors, have also been reported [14, 15]. In these cases, however, the active components use organic semiconductors or conducting polymers that are sensitive to environmental contamination and which show inferior electrical performance compared to metals and single crystal inorganic materials. The integration of such established materials with textiles have been frustrated, in the past, due to their fragile and rigid characteristics. By using non-coplanar deformable bridge structures and ultrathin active devices, these problems can be avoided. Such stretchable circuits on fabric, as shown in Fig 3, are compatible with random deformation of fabric. And even after bending (bending radius ~ 5mm), the inverter functioned well, as shown in the right bottom frame of Fig 3. By utilizing the circuits on fabric, the smart fabric can be realized for various applications, such as the wearable computer.

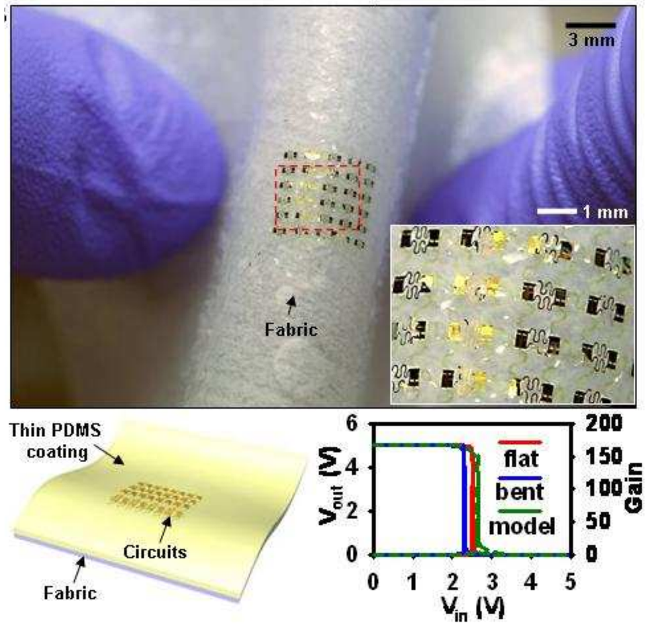

Figure 3: CMOS inverters integrated on fabric coated with PDMS (top), its schematic illustration (left bottom) and voltage transfer curves of CMOS inverters on fabric and PSPICE simulation; inset shows the magnified view of circuits. Adapted from ref. [20]

One application of wearable electronics might involve integration on gloves. We demonstrated our stretchable CMOS inverters at the finger joint of a glove, to demonstrate integration on the most challenging region. Two types of gloves, vinyl and leather were used, as shown in the Fig 4(A) and (B), respectively. For both cases, thin PDMS was coated on the surface of gloves and ultrathin inverters were transfer printed. When the fingers move, inverters are stretched or released. The deformable bridges accommodate the external strain due to stretching and prevent mechanical failures. We performed stretching tests with inverters on a leather glove by moving the fingers repetitively. Even after 1000 cycles, the electrical properties showed little variation as shown in Fig 4(C). For example, the inverter threshold voltage changed by less than ±0.4V and the gain value less than ±5%.

Another interesting possibility is CMOS integrated circuits on paper. Portable electronics in light-weight forms, designed for mass-production applications require particular substrates, such as a paper. The low cost and environment friendly characteristics make paper attractive as a substrate of future flexible electronic systems. Due to these attributes, several groups have examined routes to fabricate circuits on paper, mostly based on organic semiconductors [16-19]. The low temperature processing requirement and the flexibility of paper substrate make it difficult to utilize other semiconducting materials, such as single or poly crystalline semiconductors. By using stretchable ultrathin circuits transferred on PDMS coated paper, CMOS circuits based on single crystal silicon can be integrated on the paper. After embedding CMOS inverters on paper, a series of bending, folding and unfolding test was carried out and electrical performance was characterized, as shown in Fig 4(D) and left frame of Fig 4(E). Also cycling tests following this sequence up to 1000 times with inverters on paper suggested a robust

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construction (inverter threshold voltage change < ±0.4V, gain change < ±10%.) (right frame of Fig 4(E)).

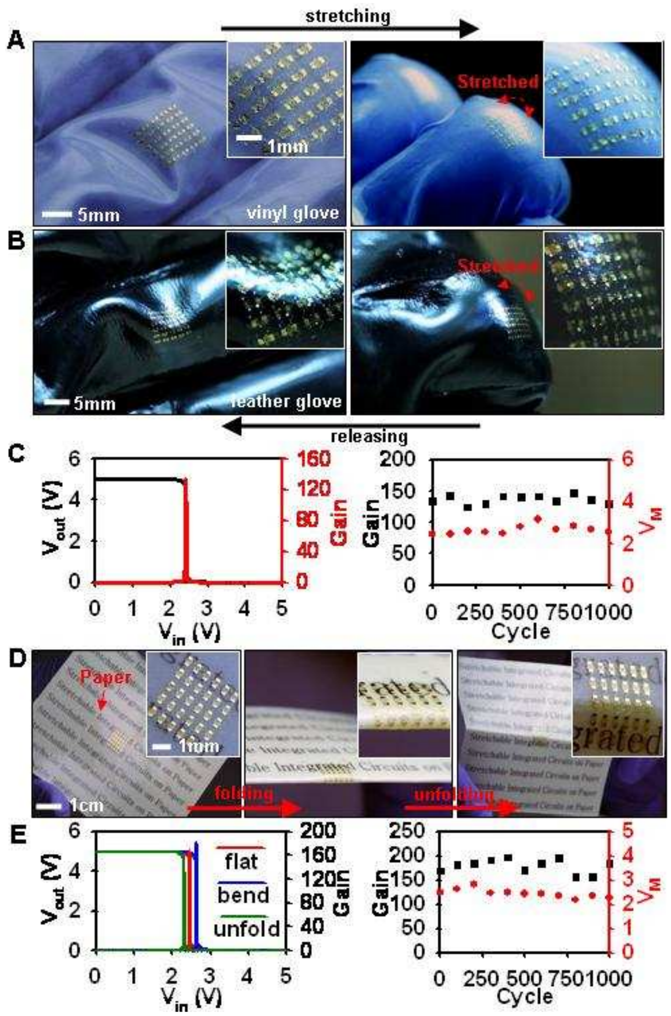

Figure 4: Optical images of CMOS circuits on finger joints of vinyl (A) and leather (B) gloves in released (left) and stretched (right) states. The insets provide magnified views. (C) Voltage transfer curve (left) and cycling test results that show the gain and threshold voltage of the inverter (V_M) measured in the flat states after various numbers of bending cycles (right). (D) Optical images of CMOS inverters on paper, in flat (left), folded (center) and unfolded (right) states. The insets provide magnified views. (E) Voltage transfer curve (left) and cycling test results that show the gain and threshold voltage of the inverter (V_M) measured in the flat states after various numbers of folding/unfolding cycles (right). Adapted from ref. [20]

CONCLUSIONS

In conclusion, the combined use of non-coplanar serpentine mesh designs with thin, low modulus strain isolation layers enables the integration of single crystal silicon CMOS integrated circuits on fabric, gloves and papers. Non-coplanar and deformable bridge structures accommodated applied strain induced by various deformations including extreme bending and folding. In addition, systematic and repetitive stretching tests up to 1000 times on gloves and

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foldable papers demonstrated the electrical and mechanical validity of stretchable CMOS circuits. Further optimization of the serpentine geometries has the potential to yield additional improvements. An important practical advance over previous reports is that procedures of prestraining to form non-coplanar layouts are not necessary. As a result, with the mechanics, materials and processing approaches reported here, commercial, product-level applications in wearable and disposable personal electronics might be possible, with significant, new business opportunities.

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