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Stretchable Printed Circuit Board Meets Stretchable Light Emitting Gallium Nitride

Arka Mukherjee[1,2*], Ahmed Hassan Gohar[1,2*], Luis F Centeno[1,2], Leslie Schlag[1,2], Nishchay A Isaac[1,2], Alper K Soydan[1,2], Pedro H O Moreira[1,2], Jörg Pezoldt[1,2] and Heiko O Jacobs[1,2]

[1]Fachgebiet Nanotechnologie, Institut für Mikro- und Nanoelektronik, Fakultät für Elektrotechnik und Informationstechnik, Technische Universität Ilmenau, Gustav-Kirchhoff-Str. 1, 98693 Ilmenau, Germany

[2]Zentrum für Mikro- und Nanotechnologien MacroNano, Technische Universität Ilmenau, Gustav-Kirchhoff-Str. 7, 98693 Ilmenau, Germany

ABSTRACT

The human body is a dynamic three-dimensional soft entity. Metal lines in commercially available electronic devices are mechanically flexible yet insufficiently deformable, enabling rigid circuits with excellent electronic characteristics but limited compliance to mechanical stress. Future electronics need to be independent of rigid electronic components to adapt to anatomical movements. Recent interest in elastic printed circuit boards (E-PCB) has been enhanced by their potential applications in skin electronics, implant electronics, electronic bio-interfaces, electronic muscles, and stretchable electronics. The new concept of metamorphic electronics involves circuits printed on a substrate that can dynamically change shape in response to external conditions. The term "metamorphic electronics" is inspired by the biological process of metamorphosis which represents the evolution of living organisms after birth. Systematic investigation of two aspects is required to ensure a longer lifetime of stretchable electronic devices:

- Stretching capability of each component in the devices is required, and
- Seamless integration of inorganic, energy-efficient components into the deformable active matrix.

In this paper, we discussed the fundamentals of metamorphic electronics implementation of a single stretchable metallization layer to achieve a reliable, industry-compatible stretchable printed circuit board (SPCB), the challenges and its applicability in modern-day electronics. As well as fabricating stretchable type III-nitride semiconductor optoelectronic devices and assembling these devices on S-PCBs. These S-PCBs show a stretchable (260%) active matrix. We will also discuss the challenges in fabricating and assembling these devices on the SPBBs. We will discuss frontiers, challenges, and prospects for stretchable metamorphic electronics.

***Corresponding author**

Arka Mukherjee, Fachgebiet Nanotechnologie, Institut für Mikro- und Nanoelektronik, Fakultät für Elektrotechnik und Informationstechnik, Technische Universität Ilmenau, Gustav-Kirchhoff-Str. 1, 98693 Ilmenau, Germany, Zentrum für Mikro- und Nanotechnologien MacroNano, Technische Universität Ilmenau, Gustav-Kirchhoff-Str. 7, 98693 Ilmenau, Germany.

Ahmed Hassan Gohar, Fachgebiet Nanotechnologie, Institut für Mikro- und Nanoelektronik, Fakultät für Elektrotechnik und Informationstechnik, Technische Universität Ilmenau, Gustav-Kirchhoff-Str. 1, 98693 Ilmenau, Germany, Zentrum für Mikro- und Nanotechnologien MacroNano, Technische Universität Ilmenau, Gustav-Kirchhoff-Str. 7, 98693 Ilmenau, Germany.

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Introduction

Research in the field of electronics has evolved in distinct phases. After achieving compactness and efficiency, recent research has shifted towards the flexibility of electronic systems. Such bendable as well as stretchable electronic systems have been developed in recent years. The realization of electronic devices and systems with performance equal to the established electronics that use rigid substrates, but stretchable and light-weight formats enable various new applications [1]. The capability to fabricate and integrate flexible, stretchable, and conformal metamorphic electronics is of much importance due to its pervasive and broad range of applications. The applications of this kind of electronic device can include smart clothing, wearable electronics, stretchable LEDs, PCBs, sensors, and flexible health monitoring devices [2]. Mechanical stretchability is essential for the seamless integration of electronics into daily life and other applications where traditional rigid electronics are insufficient [3].

This paper discusses the process of designing, fabricating, and characterizing a stretchable electronics system that integrates a stretchable Printed Circuit Board (PCB) with stretchable Gallium Nitride LEDs. Advancements in the field of stretchable electronics have paved the way for many applications where conventional rigid electronics are insufficient. However, achieving reliable electrical and mechanical performance under sufficient deformation remains a key challenge. In this work, we address these challenges by developing a system where stretchable PCB serves as a substrate for mechanically flexible GaN LEDs. The paper explores this novel hybrid stretchable electronic system's materials, fabrication, and integration. Fabrication techniques of stretchable substrates and printed circuit boards are more interesting and developed. There has been research on the development of stretchable substrates while mounting conventionally available rigid Surface-Mount Devices (SMDs), where the substrate serves the main flexibility and its interconnects solely and the SMDs do not contribute to the stretchability of the system [3]. Although this system performs well in achieving stretchability, the SMDs' rigidness limits the flexibility of the entire system by shifting all mechanical responsibility onto the metallic interconnects. This paper explores the novelty of introducing mechanically flexible SMD i.e. GaN LEDs onto the stretchable substrate. These LEDs consist of GaN P and N-type regions with gold as electrodes on each region. In stretchable electronic systems, metallic interconnects or electrodes play a primary role in the flexibility, while in this work, the gold electrodes as well as the bulk GaN regions hold the capability to accommodate stressed deformation [2]. One of the highlights of this paper is the ability of GaN to become mechanically flexible. GaN is a III-V compound with a direct band gap of about 3.4 eV. It has a hexagonal wurtzite structure and is a tetrahedrally coordinated binary compound [4]. The novelty of this work is to realize a GaN LED design that is, despite of its crystalline nature, capable of being mechanically stretchable and then the integration of these LEDs onto the receiving substrate (PCB). Regarding the integration and attachment, the metallic contact pads of both PCB and GaN LEDs are dispensed with liquid solder. This solder point will function as the joint between both electronic components.

The fabrication process also plays a vital role in achieving a stretchable electronic system. Fabrication of these devices can be done in two separate ways: i) using flexible and stretchable substrate at the beginning of the process, or ii) delaying the introduction of the stretchable substrate while performing the whole fabrication process on a temporary rigid substrate [3]. This paper discusses and uses the latter approach of delaying the introduction of the stretchable substrate until the end of the procedure. The main reason this approach is preferred in the fabrication of similar devices is that many processes like elevated temperature treatment, accurate alignment and established laboratory apparatus like spin coatings and fixation are more efficiently performed onto rigid substrates.

Experimental Section

The fabrication of GaN is done on a 1x1cm^2 chip which consists of a silicon substrate with epitaxially grown GaN on top as shown in Figure 1(a1). The epitaxial sequence of the GaN layers onto the substrate is: AlN nucleation layer, AlGaN buffer layer, undoped GaN, N-type GaN, MQWs, and P-type GaN on the top. The first step into the fabrication process is the realization of P and N-type regions. It is initiated by a first lithography step performed on MLA 150 (Heidelberg Instruments). This step selectively exposes the top P-type layer of GaN which is then etched to access the underlying N-type layer. ICP (Inductively Coupled Plasma) etching is done on Multiplex ICP STS system with 45 sccm Cl_2, 20 sccm Ar, 0.5 Pa pressure and 300W ICP power for 5 minutes. This dry etching process results in 620 nm depth and enables the formation of distinct meander-shaped P-type region as shown in Figure 1(a2).

On top of both P and N-type regions the metal electrodes are deposited by E-beam evaporation in CS400ES Ardenne system followed by a liftoff. Figure 1(a3) shows metallization on meander structures. 20 nm Cr is used as an adhesion promoter between GaN and metal whereas 300 nm Au on the top acts as the metal electrode for electrical connections. To improve the metal-semiconductor interface and reduce the contact resistance, thermal annealing is done by treating the chips at 400°C for 1 minute in the presence of O_2 [5]. Post-metallization thermal annealing improves the contact by reducing the barrier height, interface defects and leakage currents [6]. After metal tracks deposition onto both P and N-type GaN, the unused surroundings of N-type region etched by dry etching. This etching is referred to as MESA etching which results in a complete meander-shaped LED as shown in Figure 1(a4). This etching process is done as ICP (Inductively Coupled Plasma) etching with the same equipment and recipe for 30 minutes to etch 2μm of N-type GaN. Completion of this etching process results in the appearance of underlying Si carrier substrate. To reduce the thickness of the silicon substrate layer, backside deep reactive ion etching (DRIE) is done to etch 100 μm of the silicon layer. DRIE provides excellent control over uniformity and etching rate. This makes it preferable for thinning of silicon substrates [7].

Stretchable PCB serves as a receiving substrate with copper meander interconnects on which the GaN LEDs are to be transferred and mounted. The fabrication of stretchable PCB is done on-hard carrier fabrication, which means the entire fabrication process is performed on a hard-carrier and then it is eventually peeled-off at the ending steps. The schematic diagram of the entire substrate is shown in Figure 1(b), which points out all the stacks and the meander structure for the connections. This methodology is beneficial as it enables high-temperature processing and better alignment throughout the fabrication. 4-inch Boroflat glass wafer is used as a temporary hard carrier for this purpose. The first step in the fabrication of PCB is the spin coating of PMMA (Poly(methyl methacrylate)) and PI (Polyimide) onto the glass wafer respectively. The PMMA-PI interface plays a crucial role in the separation and peeling-off process as PMMA and PI act as release and peeling layer respectively. The PI layer acts as mechanically flexible peeling foil, as it has low adhesion to PMMA but strong adhesion to metallic layers [3]. PI is then cured in a Carbolite oven in the presence of N_2 at 2000C for 5 hours which reduces the residual solvent and water content that may cause outgassing [8]. For the formation of copper interconnects, firstly the 200 nm thin copper layer is deposited onto PI in a CS400ES Ardenne system by sputtering. This thin layer acts as a copper seed layer onto which lithography is performed for the pattern of meander-shaped interconnects. The use of AZ10XT positive photoresist in this lithography results in a 6.5μm high vertical sidewall structure which is sufficient for the growth of thick copper interconnect in further electroplating process. The electroplating of the copper meander-shaped is done by immersing the wafer in an acidic copper sulphate solution and providing the input current of 2.6 mA. 1 hour and 30 minutes of electroplating results in 4.5μm thick copper interconnects. Later, the photoresist is stripped and 200nm thick seed layer of copper is etched, resulting in copper meander interconnects laying on top of the PI layer. To embed the meanders structures into a flexible polymer, PMMA is spin-coated onto the wafer. Although a single layer of PMMA spin coating results in 3.5 μm thickness, the PMMA mimics the surface profile of the wafer and covers the entire copper interconnects. For characterization and mounting of GaN LEDs on the top, contact pads of copper interconnects must be exposed through PMMA. This is achieved by Reactive Ion Etching (RIE) of PMMA on the pad sites. This dry etching is done on the RIE 320 STS equipment with parameters: 50 sccm O_2, 50W power, and 50 mTorr pressure. 30 minutes of RIE results in the removal of 3.3μm PMMA from pads sites. Optical analysis using of Nikon optical microscope and depth measurement by Alpha-Step profilometer (KLA) confirm the completion of etching and exposure of the underlaying copper.

The process of integrating PCB and GaN LEDs includes solder dispensing on the exposed contact pads of PCB and mounting of LEDs on these contact sites. Liquid solder is dispensed onto the sites of PCB by immersing the wafer into a beaker of DI water with pH 2 at 65^{0}C. Glass pipet is used as a dispensing tool to make the liquid solder attach to the exposed copper sites of the PCB. These solder pads act as joint sites for the PCB and GaN LEDs. Nikon microscope and Alpha-Step profilometer (KLA) are used to analyse the structure of dispensed solder. The transfer of GaN LEDs to the PCB can be achieved by liquefying the solder at 65^{0}C in pH 2 DI water and aligning the GaN LEDs accurately onto the solder sites. The GaN layer is on top of the Si carrier substrate, so the Si is to be removed from the entire chip. Before the transfer of GaN chips to the PCB, Si is anisotropically etched in chlorine-based ICP plasma etching. This etching step results in pillars like structures which hold the GaN meander on the top. The future process is to etch out these thin pillars in isotropic wet etching to separate the entire bulk Si carrier substrate from GaN meanders. This will result in only the GaN meanders laying onto the assembly sites of Cu meanders of the PCB.

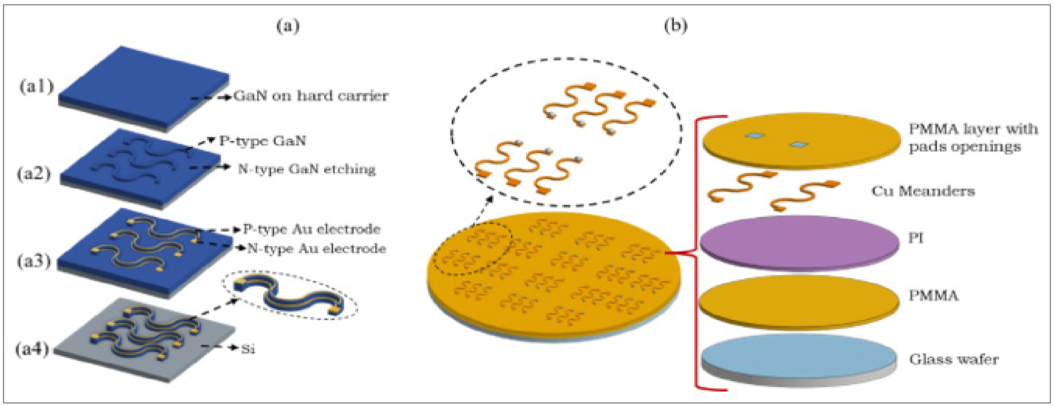

Figure 1: Schematic representation of fabrication process for GaN LEDs and Stretchable PCB. (a) Chip structure (a1), formation of P-type region by plasma etching (a2),deposition of Au metal tracks on the meanders which serves as P and N-type electrodes (a3), Mesa GaN etching to form N-type region and meander structure (a4). complete etching of GaN from the substrate except the meander structure. and (b) layer-by-layer representation of stretchable PCB fabrication which shows PMMA and PI coatings on glass wafer, followed by formation of Cu meander metallic tracks and their encapsulation in PMMA with Pads openings and solder dispensing

Results and Discussion

Figure 2 describes the meander shape GaN LEDs. Figure 2(a) shows the schematic diagram of the GaN meander structure. One meander is 5 mm long and has a width of 100 µm. Figure 2(b) shows the microscopic image of the GaN chip with multiple meander structures. The Au contact lines for both P and N-type are fabricated all across the meander to give a better contact with the respective layers. Figure 2 (c) and (d) show the Scanning Electron Microscope (SEM) image of the top and side views of the meander structure respectively to give a detailed understanding of the fabricated GaN meander, which shows P and N-type layers as well as Au contact pads. Figure 2(d) shows a magnified image of one of the contacts (Cr/Au pads which is square in shape and has a dimension of 85 μm^2. The contact pad is constructed on a square GaN structure of a dimension of 120 μm^2. The side view mesa structure gives us the insite of the topography after the ICP chlorine-based dry etching as discussed in the experiment section. As we can see the etching results in a smooth vertical mesa side wall with a height of 4.4 µm which is essential for the GaN LED fabrication [9]. The inset image also confirms the finding at a different location near the contact pads. Figure 2(e) shows the elemental composition of the GaN meander structure via SEM EDAX mapping. The elemental mapping illustrates the spatial distribution of silicon (Si), gallium (Ga), nitrogen (N), and gold (Au) across the fabricated samples. Distinct colours are used to enhance the visualization of elements: purple for Si, grey for N, cyan for Ga, and gold for Au. The elemental mapping of Si depicts the presence of Si on the substrate apart from the meander which is due to the etching of GaN as discussed in the experimental section. The homogeneous distribution of Si across the analysed region proves that whole fabrication process preserved the integrity of the Si substrate. This is further supported by the Ga and N elemental mapping which is just reciprocal of that of Si. Ga and N is present only at the desired P and N-type regions which contribute to the combination of charge carriers from both regions and makes the LED to light up. The elemental map and sharp boundaries of Ga and N illustrate minimal diffusion into the adjacent layers and the formation of a stable GaN layer. The gold colour map clearly shows the primarily localized distribution of gold on the top electrode region. The absence of significant overlap with other regions suggests accurate patterning during the fabrication. Figure 2(f) shows the image of GaN meander lighting on a hard carrier. A voltage of 9 V has been applied between the P and N-type contact pads via probes to light the GaN meander LED on hard carrier as shown in the figure. The inset shows the zoomed-in image of the LEDs using microscope. The images show after the entire fabrication process the GaN layer is perfect, and it does not affect the property of the GaN.

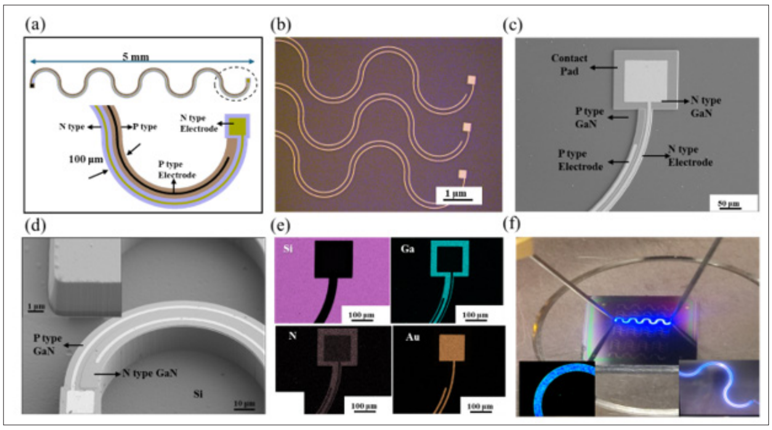

Figure 2: Schematic, microscopic, SEM, EDAX and lighting up images of the fabricated GaN LEDs. (a) Schematic image of a GaN meander showing the dimension and location of each component, (b) Optical microscope image of the meanders with P-type etching and metallic track deposition, (c) SEM image showing a magnified contact pad, metallic electrodes, P and N-type regions, (d) angled

view in SEM image showing the oblique and angled view of GaN meander on Si substrate and demonstrates overall performance of etching in achieving vertical sidewall structure, (e) EDAX image showing elemental mapping of Si, Ga, N, and Au at a magnified contact pad of GaN LED, (f) image of a lighting up GaN LED meander by applying voltages at contact pads

To investigate the stretchability of GaN with meander shaped design, Finite Element Analysis (FEA) is being done. COMSOL Multiphysics is the simulation tool used for the theoretical analysis of the stretchability of GaN. Studying the stretchability of GaN is significant as it provides theoretical knowledge and understating of how GaN LEDs would behave under certain stress conditions. This analysis is beneficial in the field of stretchable electronics, sensors, or LEDs. FEA is beneficial in evaluating stress adaptive behaviour as well as distribution of stress within the meander. This understanding enables to identify regions with higher and lower stress. Figure 3 shows the stress distribution-related computational analysis. Figure 3(a) shows a schematic diagram of the meander used for the analysis which has a width of 50 µm and thickness of 4.8 µm with an amplitude of 1200 µm and diameter of 500 µm. The total length of the GaN meander is 5mm, which is stretched up to 10% i.e. 0.5mm in stress profile analysis. One end of the meander structure is fixed while other is moved to stretch the GaN LED. The Figure 3(c) shows that the top and bottom curved parts of the meander loop are the regions with highest stress. These points undergo stress of 3.5×10^9 Nm^{-2}, and it is corresponding to the elongation direction. Whereas the middle points which join the meander loops, and the pads undergo lowest level of stress i.e. 0.5×10^8 Nm^{-2}. One of the key features of meander shaped structures is that it enables stretchability. Since the GaN crystal itself is not inherently stretchable, the meander track goes through some deformation and tries to straighten to accommodate the applied stress, which makes it a stress-adaptive design [2]. Hence, the stretchability and deformation depend on the material and geometry of the meander design. Theoretical stretchability analysis consists of COMOL Multiphysics simulations, which contain structural stretching as well as 3D mesh modelling of the meander design shown in Figure 3(b). A mesh analysis is critical in Finite Element Analysis as it discretizes a domain into smaller and manageable domains and elements [10]. In COMSOL simulations, the mesh structure determines how a geometry is divided and how the size, shape and density of elements impact the efficiency and accuracy of computational analysis [11]. It provides insight into the spatial resolution of the simulation and represents how smaller and discrete areas of GaN meander behave under external stress. These simulations show 10% stretchability of GaN meanders without the substrate. The magnified regions in Figure 3(c) indicate the stress-highlighted regions of the structure i.e. regions with highest and lowest stress. Considering the amount of stretchability of current meander design of GaN, there are some material properties which limit the stretchability up to 10%. The mechanical and material properties of GaN affect the results of stretchability experiments. The high mechanical strength of GaN limits the flexibility threshold [12]. GaN is a crystalline semiconductor with a wurtzite structure which strongly influences the mechanical and crystal properties. This type of structure is hexagonal which contributes to unique mechanical characteristics and high rigidit [13]. Considering the young's modulus which is measure of the material's stiffness under a certain stress, the COMSOL simulations and theoretical analysis show that the young's modulus of GaN is 3.3×10^{11} Pa, which is in the category of high young's modulus. Another property of GaN influencing the nature of stretchability is the Poisson's ratio. This ratio offers the metric by which the performance of any material can be compared when it is strained elastically [14]. According to the FEA, the Poisson's ratio of GaN is 0.185, which is relatively low. This low Poisson's ratio indicates lower transversal deformation when longitudinal stress is applied. This characteristic results in limitation in stretchability and flexibility of the GaN structure. These parameters determine the nature of GaN slight stretchability while maintaining its inherent properties and rigidity. One key

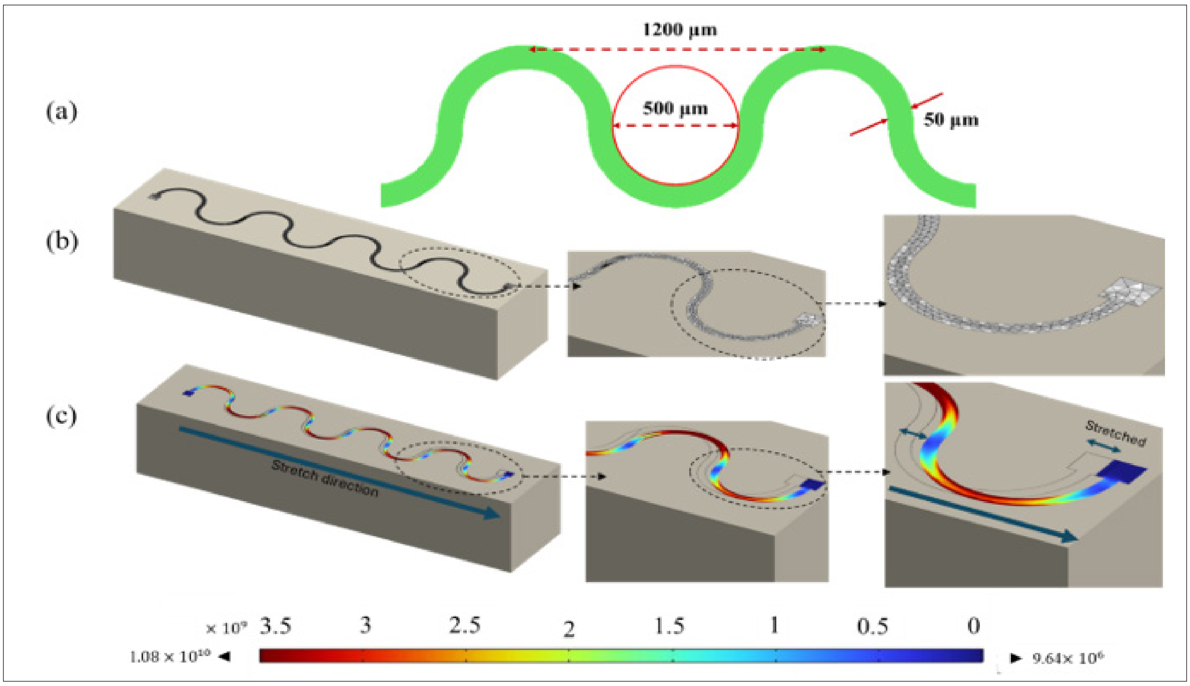

Figure 3: FEA of GaN meander using COMSOL Multiphysics. (a) schematic representation of top view of GaN meander showing its diameter, amplitude and thickness, (b) 3D mesh model implementation with magnified images of the meander curve, (c) stress distribution of the system under 10% stretch demonstrating regions of high and low-stress levels, stretch direction and magnified image of meander stretchability

feature that contributes majorly to the stretchability is the geometrical design of meanders. The wave like loop design has the potential to accommodate the stress with slight deformation and redistribute the stress. In spite of low ductility, these features of GaN design ensure slight stretchability by reducing strain concentrations. The deformation and stress profiles from simulations show how the interplay of geometrical and mechanical properties minimizes the material failure.

In order to make the GaN LEDs stretchable it is necessary to transfer them from hard carrier to a soft carrier. For that purpose, we have we have fabricated a receiving substrate as described in Figure 1(b). The key aspect of the transfer process is governed by the direct transfer via solder bump. Figure 4 gives us the inside of the solder bumps on the receiving substrate. Figures 4(a1), (b1) and (c1) gives a schematic representation of the substrate. The inset of 4(a1) shows the microscopic image of the receiving substrate and how GaN LED will transfer. The zoomed-in image of the electroplated Cu meander has two contact pads. The smaller pads have a dimension 80×85 µm and the bigger pads have a dimension of 300×300 µm. The smaller pads are designed for the GaN LED transfer process, and the bigger pads are for the electrical contacts. The microscopic image of the smaller contact pad is represented in Figure 4(a2) which shows a continuous electroplated Cu contact pad. To see the height profile, we have also taken profilometer measurements along the dashed line represented in Figure 4(a1) and (a2). We have confirmed the Cu meander has a height of 3.9 µm as shown in Figure 4(a3). To transfer the GaN LEDs on the receiving substrate via solder we need to dispense solder at the small contact pads while protecting the rest of the Cu meander. In order to achieve that we have isolated the Cu layer with Polymethyl methacrylate (PMMA) and then opened up a window using photolithography and plasma etching as described in detail in the experimental section. Figure 4(b1) shows a schematic diagram of the exposed Cu contact pads. We have also taken profilometer measurements along the dashed line shown in Figure 4(b1) and (b2) which is shown in Figure 4(b3). The thickness of the PMMA layer is 2.85 µm. Due to this process, the Cu in the small contact pads is exposed to solder during the dispensation process, which is shown in the schematic diagram of Figures 4(c1). The microscopic image of Figure 4(c2) confirms the selectivity of the solder dispensation. The thickness of the solder bump along the dashed line shown in Figure 4(c1) and 4(c2) is measured and plotted it in Figure 4(c3), which gives a thickness of 5.9 µm.

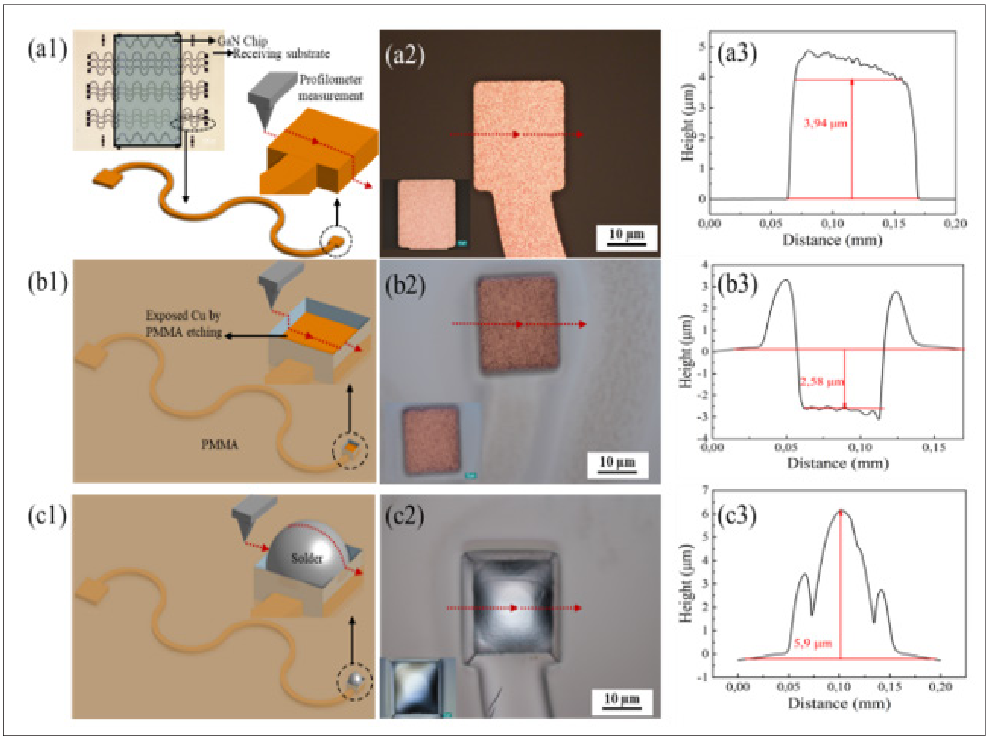

Figure 4: Schematic, microscopic and graphical images of fabricated meanders on the PCB. (a) The cu meander structure on PCB with GaN chip mounted onto it and the single Cu assembly pad structure with profilometer height measurement (a1), a microscopic image of the pad with measurement direction (a2), and profilometer measurement of the assembly pad. (b) schematic of the encapsulation of Cu meander in PMMA and etching of PMMA on pad sites (b1), microscopic image after PMMA etching showing the exposed Cu (b2), profilometer measurement showing the etching depth (b3). (c) schematic of the solder dispensing onto exposed Cu sites (c1), microscopic image after solder dispensing (c2), profilometer measurement showing the height and geometry of the solder (c3)

Future Plans

Successful fabrication, thorough theoretical analysis, and convincing results indicate that this field of work has promising potential. If the work is combined with a few more planned procedures, applying a hybrid stretchable electronic system can be advanced significantly. For that purpose, two major tasks need to be done: the transfer of GaN chip onto the stretchable PCB and removal of bulk Si carrier substrate from GaN. Then the entire surface can be embedded in elastomer. As mentioned in the experimental section, the chip can be mounted onto the assembly sites of receiving substrate (PCB) which is already dispensed with solder as shown in Figure 5(a). For that purpose, after the mounting of GaN onto the receiving substrate, we need to detach the hard Si carrier of the GaN and embed everything inside a stretchable polymer to obtain a stretchable Ecoflex PCB as described in the experimental section, already created Si pillars can be isotopically etched in KOH solution, shown in Figure 5(b) [15]. This will separate the bulk Si substrate from GaN and the resulting device will contain solely GaN meanders on top of the receiving substrate as shown in Figure 5(c). Ecoflex elastomer will be coated onto the wafer which will serve as a stretchable substrate for the PCB and it will embed the GaN meanders into it, as shown in Figure 5 (d). PMMA and PI interface acts as the peel-release layer for this purpose. After the etching of PI,

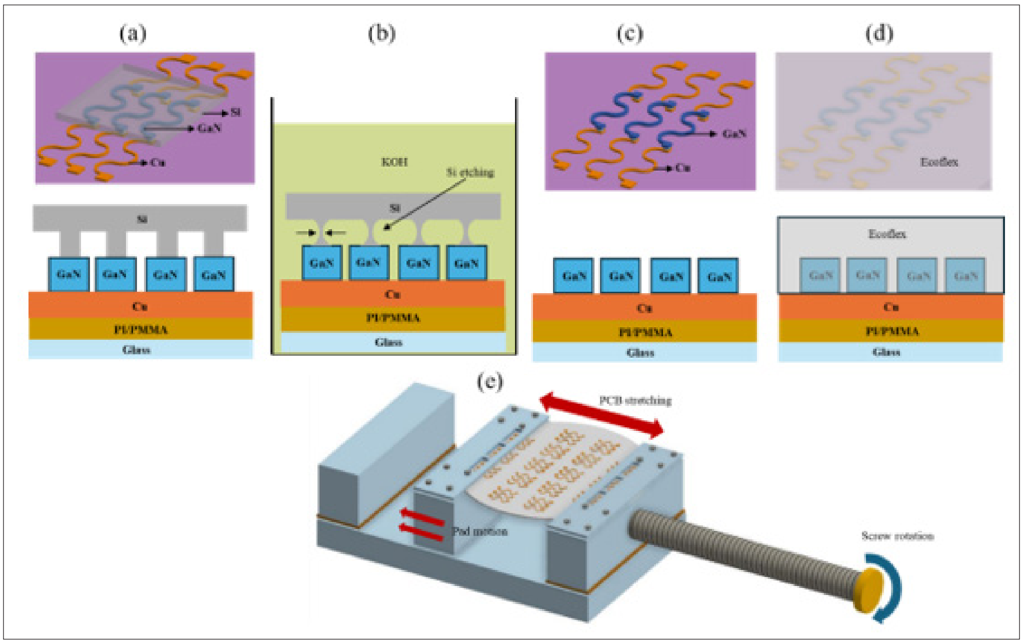

Figure 5: Long-term objective showing schematics of transfer process and stretchability setup. (a) mounting of the GaN chip with anisotropically etched Si onto receiving substrate, (b) removal of bulk Si carrier substrate from GaN by KOH etching, (c) post-etching schematic showing GaN meanders onto Cu meanders after Si carrier substrate removal, (d) coating of Ecoflex elastomer on the top of the sample which encapsulates GaN LEDs, (e) stretchability setup which will be utilized to test the stretchability of PCB and GaN LEDs. Stretchable PCB obtained after peeling-off process is to be mounted onto this setup to analyse the stretchability of the system

The next step is to characterize the stretchability of the whole PCB. The stretchability setup is shown in Figure 5(e), which consists of two screw-supported spots mechanically. One of the supports is fixed and attached to the base, while the other pad is movable. The movable pad is attached to a long screw and can be moved back and forth by rotating the screw. Meanwhile during the expansion or stretching of the substrate, electrical voltages can be applied and measured from pad openings at the same time. In this way not only the stretchability behaviour of the substrate and GaN will be observed but also the electrical characterization is possible. Mechanical stretchability, as well as electrical behaviour on different stress levels, will enable to characterize the properties of the copper meanders, GaN meanders and solder joints. Future work also refers to the characterization of stress and stretchability on different meander designs of GaN. Designs with different amplitude and curvature radius will be beneficial in comparing the efficiency of different meander shapes.

Conclusion

In summary, meander-shaped GaN LEDs and their transfer onto stretchable PCBs have been studied. In computer simulation, the stress distribution is improved by the stress-adaptive design. Higher levels of elongation in the single stretching test and more cycles in the long-term cycling test are the outcomes of the improved design. However, two shortcomings can be pointed out in the whole research. First is the fact that one kind of meander structure has been studied and how the stress adaptivity changes along with the meander structure has not been discussed. Second, only one directional stretchability is studied. However, successful fabrication procedure and lighting of the meander-shaped LEDs is a big leap towards to realization of fully stretchable GaN LEDs.

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