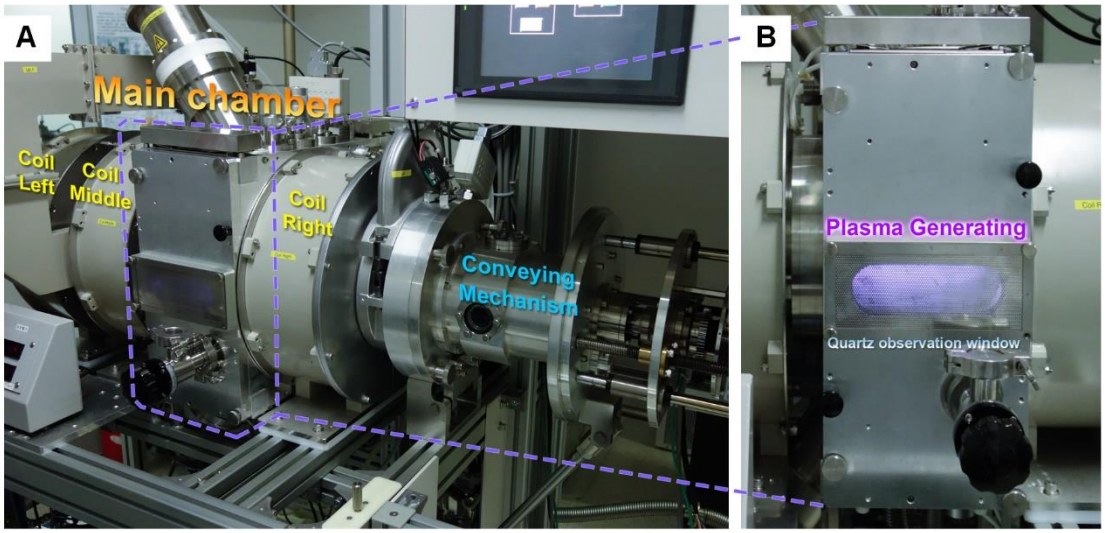
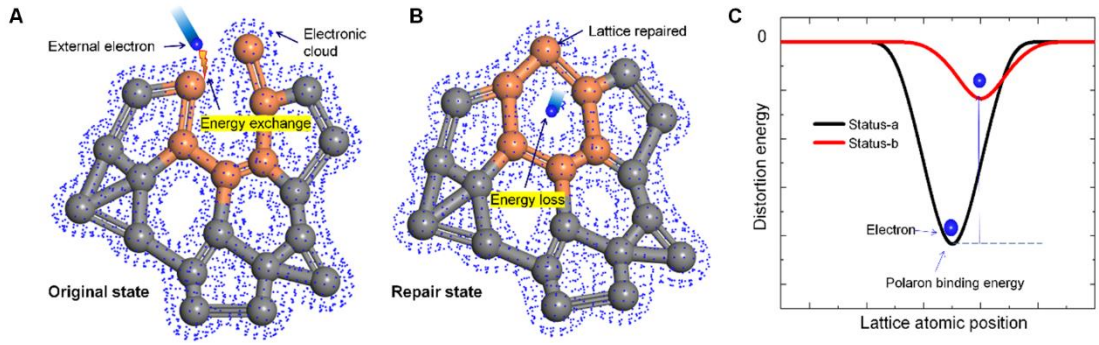
Direct fabrication of high-performance multi-response e-skin based on a graphene nanosheet film



Supplementary Figure 1. Electron cyclotron resonance (ECR) sputtering system.

The GNEC films were fabricated by using an electron cyclotron resonance (ECR) plasma sputtering system. With the assistance of the low-energy electrons, graphene nanosheets embedded in amorphous carbon grow perpendicularly to the substrate. The atomic model of three-layer graphene sheets indicates the GNs embedded in amorphous carbon. A 500W-power microwave was delivered into the vacuum chamber to generate the plasma at the argon pressure of 4×10^{-2} Pa. The mirror confinement magnetic field was applied to enhance the plasma density. A negatively biased glassy carbon target was sputtered by Ar^{+} ions to generate carbon species towards the substrate. The thickness was controlled by deposition time. The deposition time of 30 min was adopted in this work and the thickness is ~70 nm. A positive deposited voltage (V_{dep}) was applied to the substrate for attracting electrons. With the assistance of the low-energy electrons, graphene nanosheets embedded in amorphous carbon grow perpendicularly to the substrate. The electron energy was modulated by V_{dep} which affects the size and number of GNs.

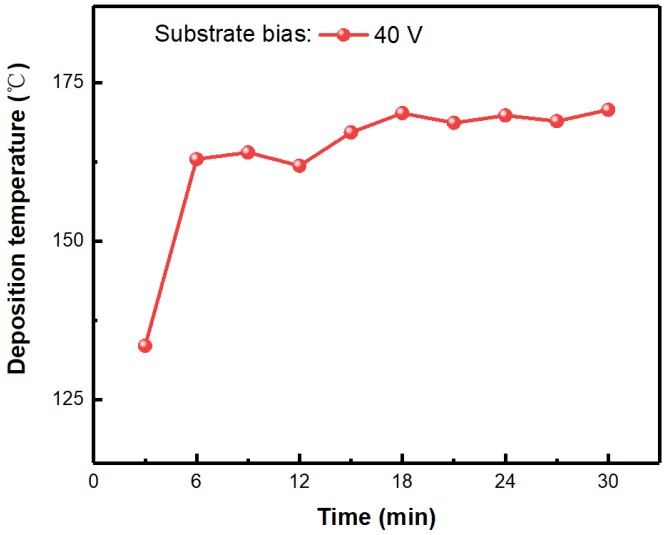


Supplementary Figure 2. The energy-transfer mode between the plasma and the substrate surface is not purely a thermal effect but a "low-temperature polariton" energy-transfer mode (A), (B). For short, the low-energy electrons in the ECR plasma interact with the lattice of the substrate surface to form polaritons. (C) The polaritons repair the neighbor lattices to form sp^2 bonds and release energies.

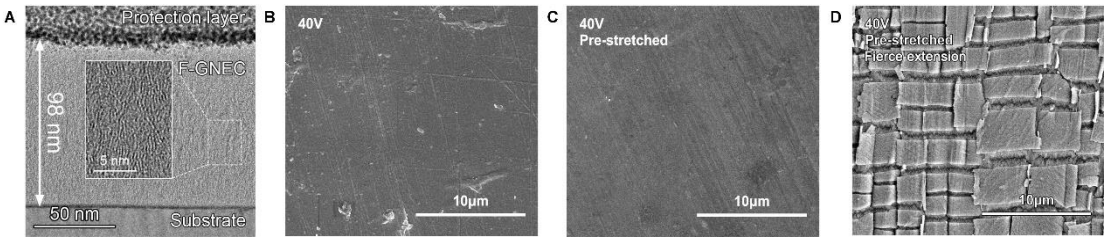
This process can be described by the following Hamiltonian:

$$\begin{cases} H_{latt} = \frac{K}{2}\sum(u_{n+1} - u_n)^2 & \text{(Lattice Hamiltonian)} \\ H_{ext} = \sum V_n(C_n^+ C_n - 1) & \text{(External field Hamiltonian)} \\ H_e = -\sum t_n(C_n^+ C_{n+1} + H.c.) & \text{(Electron Hamiltonian)} \end{cases} \quad (1)$$

Where U_n is the coordinate of the atom core in the lattice, k is the Hamonic oscillation strength. V_n is the strength of the external field of plasma and t_n is the overlap integral of electron clouds.

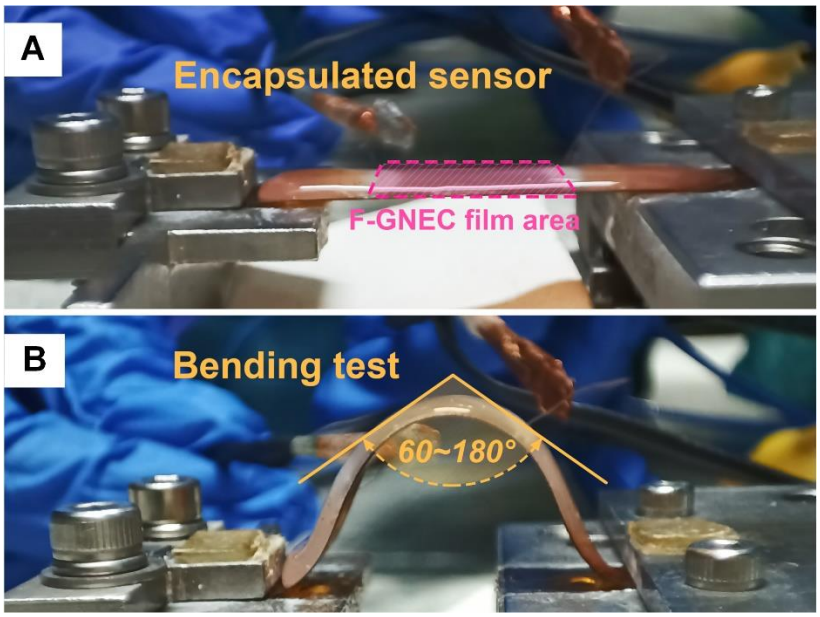


Supplementary Figure 3. Fabrication temperature under substrate DC bias of 40 voltage. A retarding field energy analyzer (RFEA)installed on the substrate holder was used to measure the radiation EEDF on the substrate surface. An infrared thermometer was installed in the discharge chamber to measure the deposition temperature by collecting the infrared radiation from the coating surface. After the plasma was turned off, the measured deposition temperature decreased at rates of 0.1–0.2 ℃/s. The error of the temperature measurement is less than 5 ℃. The plasma was turned off for 10 s when the thermometer worked, so the interference from the plasma infrared emission was eliminated. The temperature rose rapidly in the first six minutes and then stayed relatively stable, which could be due to the balance of heat dissipation and absorption of substrates.



Supplementary Figure 4. Cross-section TEM image (A) and planar SEM image of normal F-GNEC films (B), (C), and F-GNEC film under fierce extension (D).

Fig. S3a clearly shows vertically grown GNs in the cross-sectional sample of F-GNEC film, which was prepared by focused ion beam (FIB) etching. The F-GNEC film was protected by depositing a platinum layer on the surface by an auxiliary gas injection system before the FIB etching process. It can be seen that GNs grew vertically on PI substrate with a vertical thickness of about 98 nm. Fig. S3b, c presents the plan-view SEM of standard and pre-stretching F-GNEC film. Corresponding to the AFM results, the F-GNEC films have homogenous flat surface morphology in the range of about 25×25 square microns, and the pre-stretching film displayed a more uniform surface.



Supplementary Figure 5. Flexible sensor test platform for the tensile test (A) and bending test (B).

The testing platform mainly consists of two parts fixing each side of the flexible sensor. A Keithley 4200-scs semiconductor characterization analyzer was used to measure I-V curves during the bending test and bend test. The maximum range of movement is about 5cm, which allowed the sensor under 3cm length to obtain a strain of 120%.