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Supplementary Materials for

Single-crystalline germanium nanomembrane photodetectors on foreign nanocavities

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Supplementary Materials

note S1. Fabrication and characterization of the laboratory-made GeOI wafer.

The germanium-on-insulator (GeOI) wafer was fabricated by smart-cut process (*49*) as shown in fig. S1.

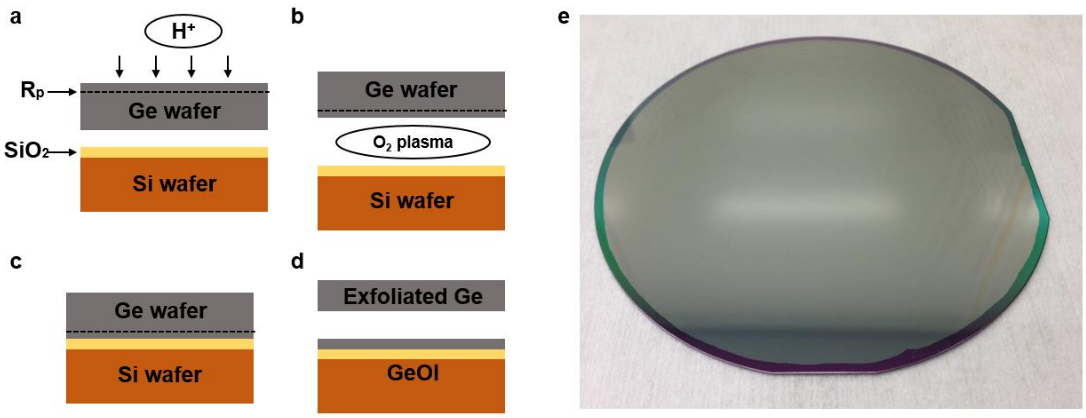

fig. S1. Fabrication process flow of 4-inch GeOI and its finished sample. Smart-cut^{TM} based process flow of the GeOI. (**e**) Lab-made 4-inch GeOI wafer.

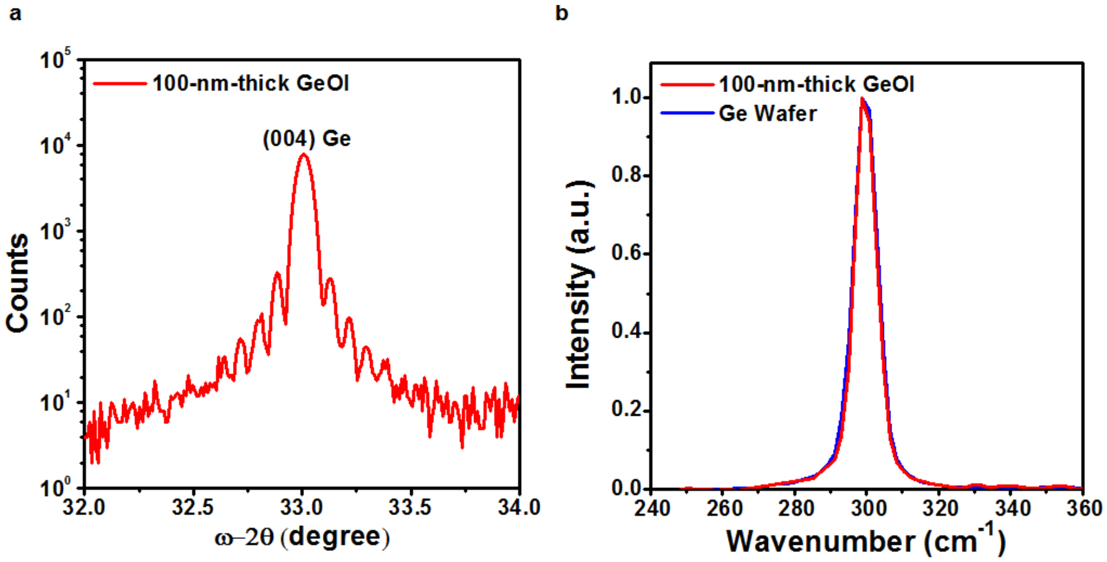

fig. S2. Characterization of laboratory-made GeOI. (**a**) High resolution X-ray Diffraction (XRD) results of the 100 nm Ge/1-µm-thick SiO_2/Si wafer. (**b**) Raman scattering result of a fabricated GeOI wafer compared with that of a bulk Ge wafer. The same peak position indicates the GeOI is strain and stress free.

To characterize the lab-made GeOI, we used the Panalytical X'Pert MRD high resolution X-ray diffraction (XRD) to characterize the single crystallinity of the Ge membrane. Figure S2a shows the XRD result of the GeOI with a peak at 33.1°, confirming the singe crystallinity. The fringes on both sides of the peak are introduced by the X-ray interference with the 100-nm-thick Ge nanomembrane. The interference fringes indicate that both sides of the Ge nanomembrane are smooth and flat. We also use the Horiba LabRAM ARAMIS Raman spectroscopy to characterize the GeOI. As shown by fig. S2b, the fabricated GeOI has the same peak location of 300.9 cm^{-1} as the Ge wafer, confirming that the fabricated GeOI is stress and strain free. We then used the van der Pauw approach to measure the carrier concentration and carrier mobility of the p-type GeOI, as shown in table S1.

table S1. Electronic properties of p-type GeOI sample.

Parameter	P-Type GeOI
Sheet Resistance (R_s)	617.7 Ω/□
Hall Coefficient (R_H)	97.9 m^2/C
Carrier Mobility (μ_p)	393 $\mathrm{cm}^2\ \mathrm{V}^{-1}\cdot\mathrm{S}^{-1}$ (hole)
Carrier Concentration	1.447×10^{18} $/\mathrm{cm}^3$

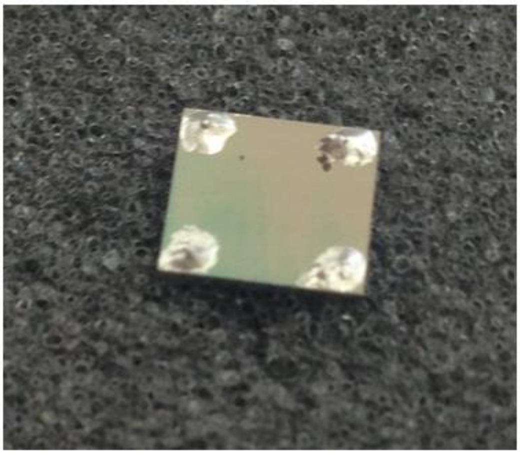

fig. S3. The GeOI sample used for the van der Pauw measurement. The silver paste is used for the electrical contact.

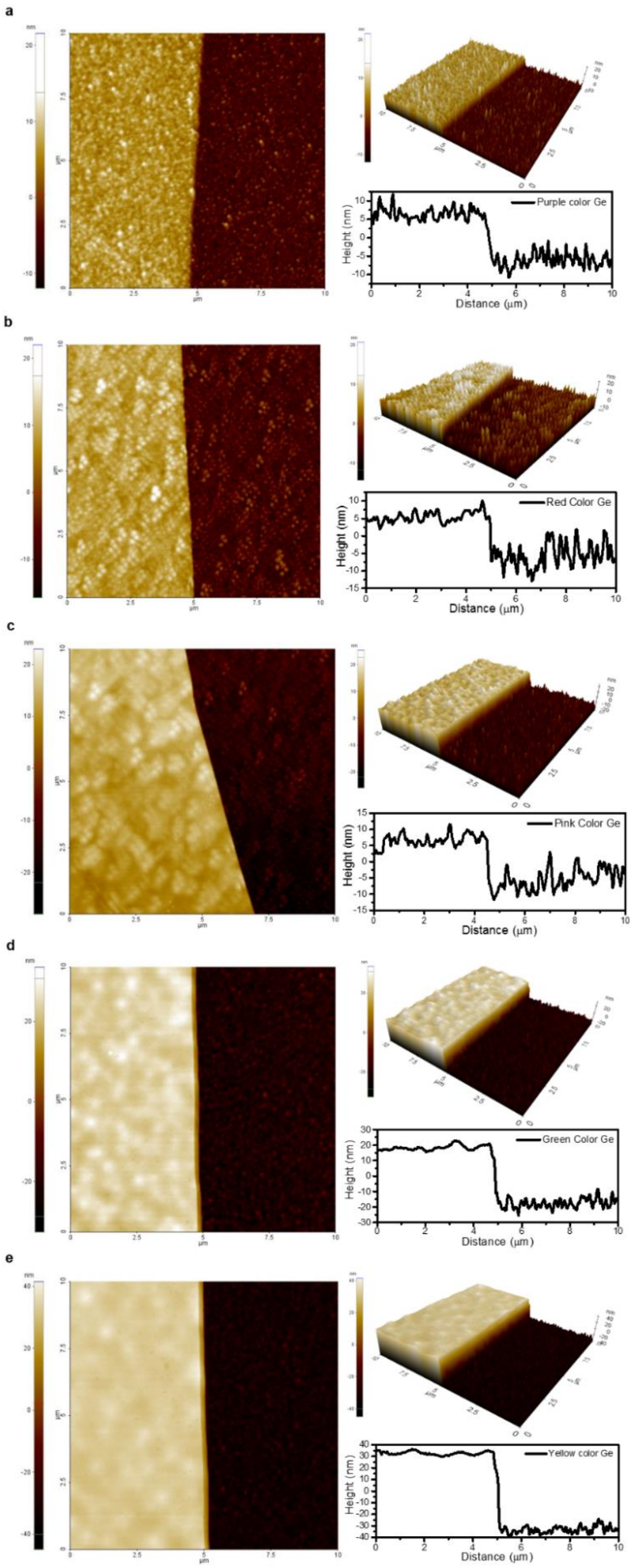

fig. S4. Thickness measurement of the corresponding ultrathin Ge membranes in Fig. 1B by AFM (XE-70 Park System). (**a**–**e**) The thicknesses of the ultrathin Ge membranes are estimated to be 10 nm, 15 nm, 20 nm, 35 nm and 60 nm, respectively.

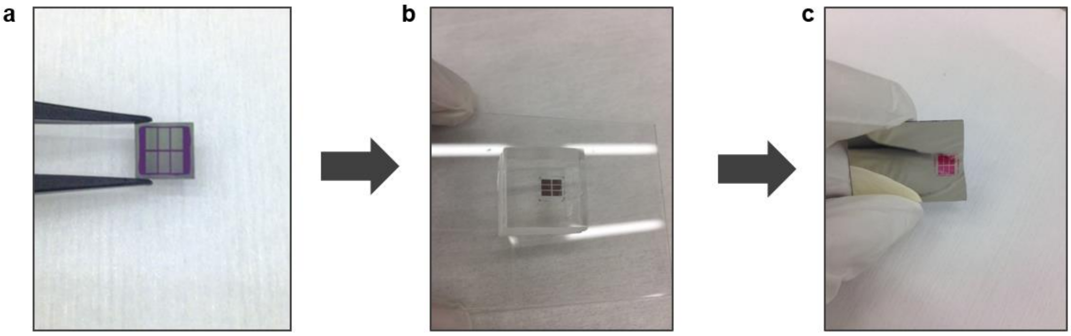

fig. S5. Demonstration of the ultrathin Ge nanomembranes from laboratory-made GeOI to foreign substrate. (**a**) The GeOI wafer was cut into 6 mm by 6 mm small pieces for the membrane transfer printing process, and was patterned by photolithography into the membrane shape. (**b**) The sample was dipped into the pure HF solution (49.1%) for 15 minutes. The Ge nanomembrane was released and picked up by a PDMS layer. (**c**) The membrane was then transfer printed onto the designed foreign substrate. A subsequent dry etching was used, with the etching pressure at 25 mTorr, the O_2 flow of 5 sccm, the CF_4 flow of 45 sccm, and the RF power of 100 W. The etching time was 60 seconds to thin down the membrane from 100 nm to 10 nm. The membrane showed red color because of the optical interference. The SEM image of the transferred membrane can be seen in the fig. S6.

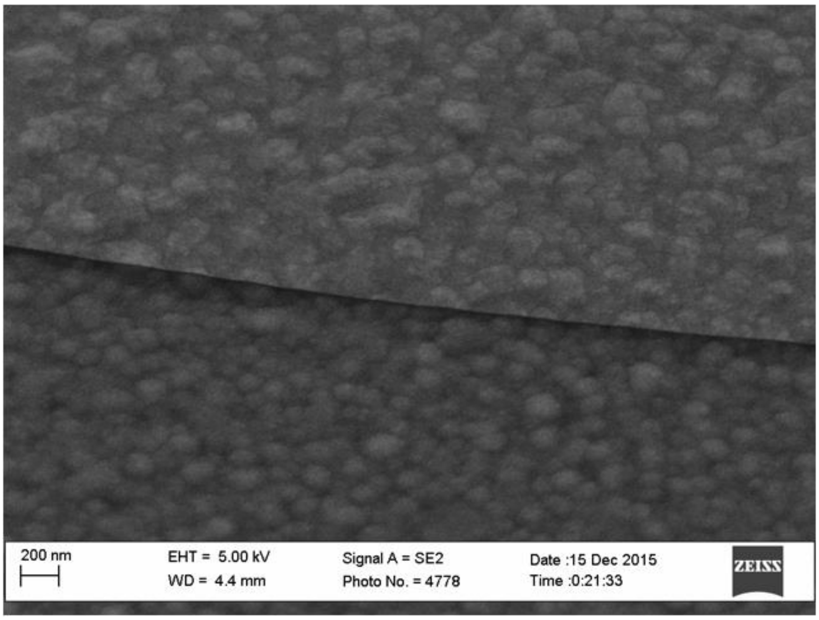

fig. S6. Titled scanning electron microscopy images of the ultrathin Ge membranes transferred onto foreign substrate. The thickness of the membrane is estimated to be around 10 nm. Since the Ge membrane is very thin, it conforms to the morphology of the evaporated Al_2O_3 - layer.

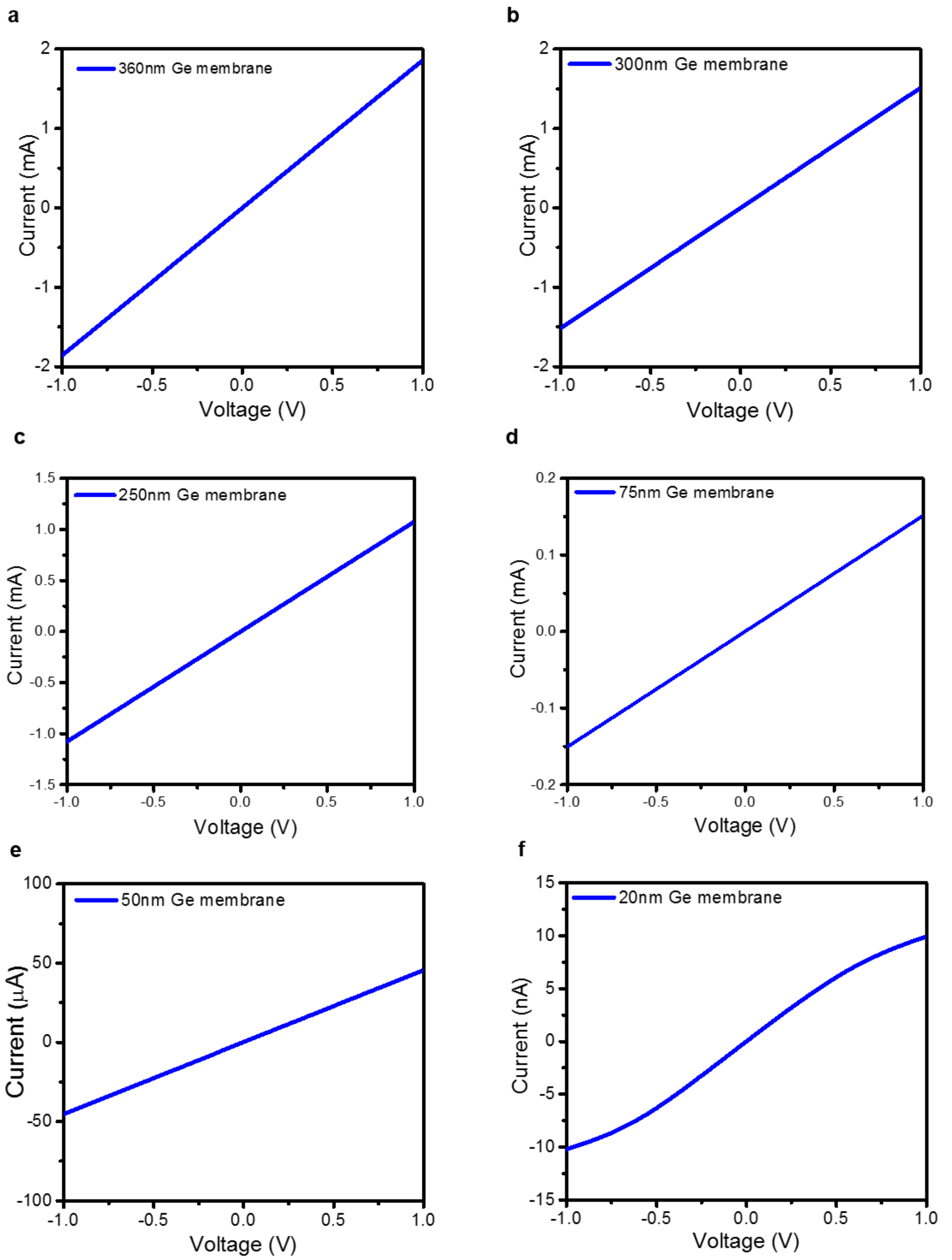

fig. S7. Dark current measurements of different thicknesses of the Ge membrane sample. (a–c) The dark currents are in the order of milliampere when the thicknesses of Ge membranes are in the order of hundred nanometers. (**d**) Dark current drops below one milliampere when the thickness is reduced to 75 nm. (**e**) Dark current decreases to tens to hundreds of microampere when the thickness is 50 nm. (**f**) The dark current is in the order of nanoampere when the thickness is 20 nm.

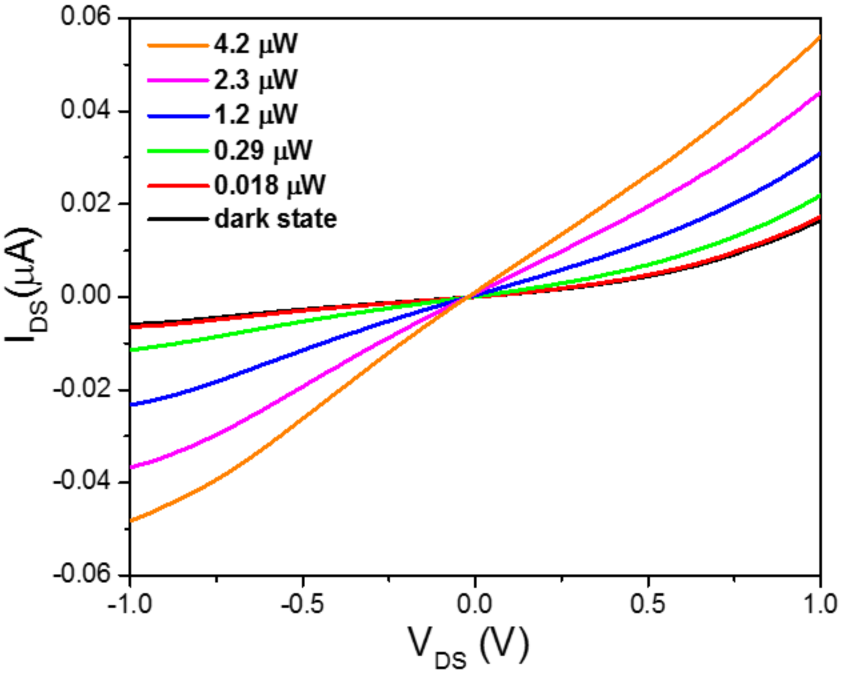

fig. S8. The dark current and the photoresponse of the ultrathin GeOI sample.

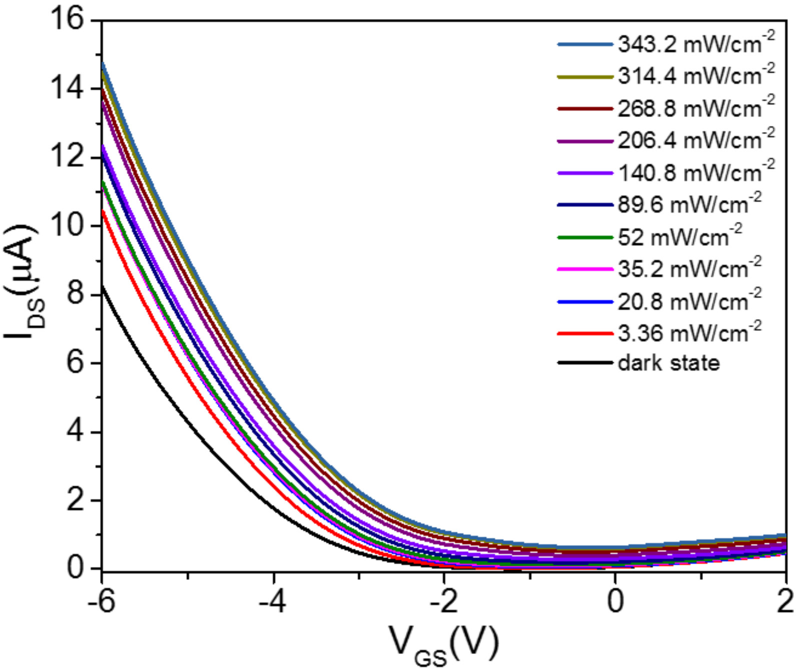

fig. S9. V_{GS}-I_{DS} curve under the dark and different illumination conditions.

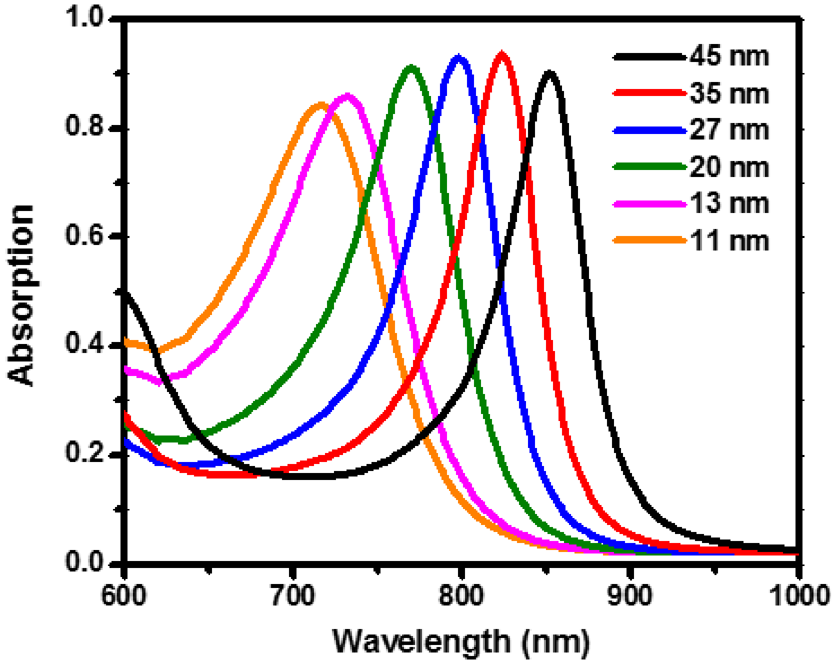

fig. S10. Simulated absorption spectra of ultrathin Ge nanomembranes on a 220-nm-thick Al_2O_3/Ag nanocavity substrate.

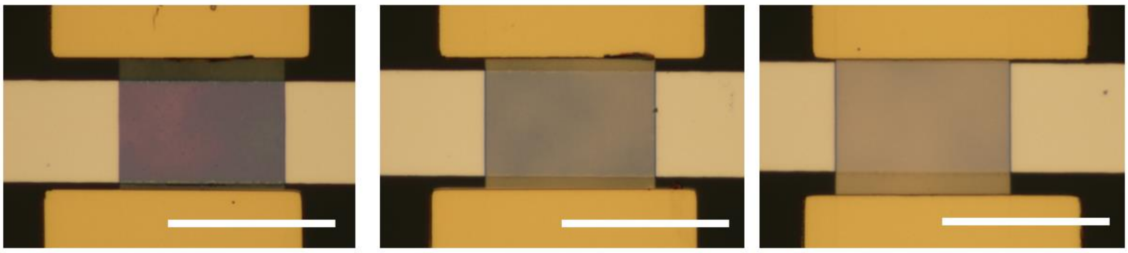

fig. S11. Optical microscopy images of the samples for multispectral response measurement. The scale bar is 50 μm.