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Suspended germanium membranes photodetector with tunable biaxial tensile strain and location-determined wavelength-selective photoresponsivity.

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A divergent microstructure was fabricated by CMOS compatible processes on the central region of a Ge *p-i-n* photodetector to enhance the residual tensile strain. Tunable biaxial tensile strain of ~ 0.22 – 1.01% was achieved by varying the geometrical factors, and it was confirmed by Raman measurements and finite element method (FEM) simulations. The suspended germanium membranes enhance the absorption across the *C*- and *L*-band (1,528–1,560 nm and 1,561–1,620 nm) and extend the cutoff wavelength to $\sim 1,700$ – $1,937$ nm. The Ge absorption coefficient is enhanced by $\sim 4.2\times$ to $2,951\text{ cm}^{-1}$ at 1,630 nm which is comparable with that of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$. Furthermore, due to the varying strain distribution on the Ge mesa, each photodetector presents the location-determined wavelength-selective photoresponsivity characteristics. This work offers a promising approach for adjusting the absorption spectra of the photodetector by harnessing geometrically amplified biaxial strain.

As an enabling material for datacom applications, germanium (Ge) has gained much interest due to its complementary metal-oxide-semiconductor (CMOS) compatibility.^{1–3} Due to the small splitting between the indirect Γ valley and direct Γ valley (~ 140 meV), Ge could change from an indirect bandgap material to a direct bandgap material by introducing a ~ 1.7 – 1.9% biaxial tensile strain,⁴ which reduces this valley splitting. Furthermore, a slight tensile strain ($<0.3\%$) in Ge also results in a redshift of its absorption edge and enabling an enhanced Ge absorption coefficient.^{5, 6} Several strategies have been reported to introduce the tensile strain in Ge material, such as epitaxial growth on the lattice-mismatched substrate,⁷ mechanical deformations,⁸ the external silicon nitride (SiN) stressor and strain amplification method on Ge/Si-on-insulator (G/SOI) platforms.^{9–14}

Recently, the external stressor layer technique and strain amplification method has been widely demonstrated to extend the absorption edge of Ge material from 1.55 to $2\text{ }\mu\text{m}$.^{9, 12} Both approaches are CMOS compatible and promising for the group-IV lasers.^{15–17} However, for the external stressor technique, the thickness of the silicon nitride layer needs to be highly controlled, and the Ge layer's strain along the depth direction is not homogeneous. Furthermore, the strain level is immutable at the stage of the wafer bonding. Thus, some groups have proposed the tunable biaxial strain method from the geometrical strain amplification technique.^{13, 18–20} Although this method has the advantages on realizing biaxially strained Ge with the valuable homogeneity and tunability, the practical application, such as laser or photodetector, remains missing.

Here, we report a tunable biaxial tensile strain Ge photodetector on germanium-on-insulator (GeOI) substrates fabricated by the CMOS compatible process. A high biaxial tensile strain $\sim 1\%$ was demonstrated in the Ge membrane from micro-Raman measurements and

FEM simulations. The extracted Ge absorption coefficient is enhanced by $\sim 4.2\times$ to $2,951\text{ cm}^{-1}$ at 1,630 nm. Due to the variable strain on the different region of the Ge mesa, the photodetector has the location-determined wavelength-selective photoresponsivity characteristics. Our result demonstrated this CMOS compatible, strain tunable technology could be useful for the realization of the wavelength tuning laser or photodetector.

FIG. 1. (a) and (b) 3D schematic of suspended germanium membranes *p-i-n* photodetector. (c) and (d) Top-view SEM image of fabricated suspended germanium membranes photodetector.

Direct wafer bonding and ion implantation were used to fabricate the vertical Ge *p-i-n* photodetector on GeOI platform.²¹ The Ge layer has a thickness of $\sim 1,200$ nm, consisting of an 800 nm intrinsic layer and ~ 200 nm *p* and *n* doping layers. Subsequently, to form the tunable biaxial tensile germanium membrane, etched slits within germanium nanomembranes were designed. As shown in the simplified schematic (Fig. 1(a)), the structure consists of an inner microdisk region with a diameter of ~ 7.5 – $15\text{ }\mu\text{m}$ with radially symmetric 32 etched slits (outer region). For these etched slits, the 8 main slits close to the disk region were used to amplify the strain, while the other 24 slits were designed to wet etch the bottom SiO_2 layer easily.¹⁸ The radially symmetric pattern structure was patterned by electron beam lithography (EBL)

followed by a dry etching using chlorine-based reactive ion etching (RIE). This dry etching was used to etch the Ge material and stop on the bottom SiO₂ layer. Subsequently, the SiO₂ below the Ge layer was removed in buffered oxide etch (BOE) solution. It should be pointed out that the etching time was carefully tuned to make sure the SiO₂ below the divergent microstructure region has been fully etched, while the SiO₂ beyond the photodetector mesa region is not etched (Fig. 1b). During the isotropic wet etch process, the small initial tensile stress redistributes, resulting in the large tensile stress at the center of each device (inner microdisk region).¹⁹ The double-mesa *p-i-n* structure and ground-signal-ground (GSG) Ti/TiN/Al electrodes were formed using standard optical lithography processes. A 260 nm SiO₂ layer was deposited on the sample, which acts as the passivation layer. The final top-view SEM images of the tensile-strain germanium nanomembranes photodetector are shown in Fig. 1 c and d. Released inner micro-Ge disk with radially etched slits can be identified.

FIG. 2. (a) and (b) FEM simulation of the strain of the suspended germanium membranes; (c) Raman spectra of the Ge in the micro disk region with different geometric design and (d) the corresponding band energy from calculation. Inset d shows breaking case due to the corner stresses.

Finite Element Method (FEM) simulations (COMSOL Multiphysics) were used to analyze the strain homogeneity. Considering the Ge stiffness matrix, a 2D linear elastic model was used, and the strain along the vertical direction of the membrane was assumed to be 0. For this simulation, an inter/outer region diameter of 7.5/160 μm and an initial strain of 0.20% in the Ge layer is considered. The final obtained strain is the equivalent in-plane defined as: $\varepsilon_{bi} = \frac{\varepsilon_{xx} + \varepsilon_{yy}}{2}$. The top view strain distribution of the suspended germanium membranes is shown in Fig. 2a and b. It can be observed that most of the Ge region has a tensile strain of $\sim 0.2\%$ except for the inter microdisk region. A detailed observation of the microdisk region in Fig. 2b shows a uniformly high tensile strain region is achieved. The microdisk region has a dominant color of orange, indicating that the surface of this region has a tensile strain of $\sim 1\%$. We also note that a yellow color region exists outside the microdisk, indicating a strain transition region between

the inner and outer regions. The strain concentration in this the microdisk region can be explained by the pulling effect of eight main etched slits. As the pulling effect on the central microdisk regions is from all directions,¹⁹ the produced tensile strain is biaxial, which is different from the suspended Ge microbridges which could only resulting into an amplified uniaxial strain.¹⁷

The strain of the suspended Ge membrane was measured and analyzed by Raman spectroscopy. The laser of the Raman system has a wavelength of 532 nm and a spot size of $\sim 1 \mu\text{m}$. As shown in Fig. 2c, the peaks of the strained Ge microdisk have an obvious left-shift compared with the GOI. The GOI sample has 0.9 cm^{-1} left-shifted compared to the bulk Ge at 300.80 cm^{-1} . By applying a strain-shift coefficient (390 cm^{-1}),²² this left shift indicates a 0.22% biaxial tensile strain exists on GOI, resulting from the thermal expansion coefficient difference between Si and Ge. For the suspended Ge membranes in the inner region, a variable left-shift ($1.18\text{--}3.18 \text{ cm}^{-1}$) is observed as compared to the GOI sample, depends on the diameter of the inner and outer region. Based on the Raman shift, the biaxial tensile strain of the inner region is tunable from 0.67 to 1.01% (0.48 to 0.67%) when the inner diameter decreases from 15 to $7.5 \mu\text{m}$ with a fixed outer region diameter of $160 \mu\text{m}$ ($80 \mu\text{m}$). The Raman results are consistent with the FEM simulations, which shows that the strain in the microdisk region depends on the initial strain and the ratio of the microdisk diameter to the outer region diameter.^{18, 19} Similar to the previous studies using the strain amplification method, the realized biaxial strain on the germanium membranes is limited to $\sim 1\%$.^{18, 19} This is because the membrane tends to break from the corner of slits (Inset Fig. 2d). The higher biaxial strains could be expected with larger dimensions by reducing defect density of the Ge layer or alleviating the corner stresses.¹⁸

The correlation between the tensile strain and absorption coverage extension due to the induced bandgap shrinkage was studied. Deformation potential theory was used to calculate the conduction band and Γ -valley heavy-hole (Γ -HH) bandgap edges as a function of the biaxial tensile strain from 0 to 1.5% .²³ The calculated direct band energy of Ge under different tensile strain is shown as the solid black line in Fig. 2d. From the band energy curve, the variable tensile strain ($0.22\text{--}1.01\%$) from suspended Ge membranes is expected to lead to an absorption edge shift to $\sim 1700\text{--}1937 \text{ nm}$ as the direct bandgap of Ge is narrower toward $0.64\text{--}0.73 \text{ eV}$.

The performance of the suspended tensile-strain Ge photodetector is shown in Fig. 3a and b. For photodetector, the mesa diameter is $250 \mu\text{m}$ with the inner and outer region diameters of 15 and $160 \mu\text{m}$, respectively. To present location-determined photoresponsivity characteristic of the photodetector, a continuous wave laser ($1500\text{--}1630 \text{ nm}$) which is connected to a $9 \mu\text{m}$ diameter single-mode fiber was used. Current-voltage curve of suspended germanium membranes photodetectors under dark and light conditions at different irradiation positions (point 1 and

2) is shown in Fig.3a. It could be observed that the dark current curve has no obvious rectification characteristics. This should be due to the damaging of the bottom p-Ge layer during the fabrication of the membrane and double-mesa of the photodetector from wet/dry etching. However, the current performance of the photodetector is stable, and the photocurrent at different irradiation positions is in line with our expectations. The same as the regular p-i-n detector, the minimum photocurrent appears after a small forward voltage.²¹ The photodetector has optical response without bias voltage (Voltage = 0V), indicating a built-in electric field electric originated from the p-n junction exists in the photodetector. Due to the decreasing tensile strain from central to edge, the photocurrent under 1630 nm light at point 2 is obviously less than at point 1. The responsivity spectra of the Ge photodetector in different irradiation positions (1, 2, 3, 4) are measured from 1,500 to 1,630 nm under a reverse bias of -1 V (Fig. 3b). By comparing points 1 and 4, it could be observed that an enhanced responsivity ($\sim 20\%$) was achieved at 1,550 nm due to the amplified tensile strain in the microdisk region. More importantly, the responsivity enhancement increases with increasing wavelength, where the photocurrents are increased by more than $\sim 100\%$ for the wavelength of >1580 nm and $\sim 300\%$ at 1,630 nm. Different from point 4, the responsivity rapidly decreased as wavelength increased, which is not observed in the measurement range for point 1. This is consistent with the above Raman and FEM analysis that this geometrical factor (inner and outer diameter of 15 and 160 μm) could lead to a biaxial tensile strain of 0.67% in the central region which extends the absorption edge to 1,788 nm. Due to the limitation of the laser source (1,500-1,630 nm), the wavelength responsivity of the detector after 1,630 nm could not be measured. Finally, the photodetector also exhibits location-determined photoresponsivity characteristics. Due to the gradually decreased tensile strain toward the edge region, the longer wavelength's responsivity (>1580 nm) shows a continuous decrease from points 1 to 4. This spatially variable photoresponsivity in a single device is different from the common photodetector with a uniform photoresponsivity. We also noticed that the wavelength tuning GaN and AlGaIn nanowire photodetectors on different devices has been demonstrated recently and suggested to be used in optical spectroscopy.^{24, 25} For these works, the strain was controlled from the nanowire size, and the fabrication process is complex as compared to our method.^{24, 25}

The absorption coefficient (α) of the Ge membrane on different position could be extracted as follow,^{6,26}

$$\alpha = -\frac{1}{t_{\text{Ge}}} \ln \left(1 - \frac{1240}{\lambda(\text{nm})} * \frac{R}{1-r} \right) \quad (1)$$

where h , v , are the Planck's constant and wave frequency, and t_{Ge} , R , and r are the thickness of intrinsic Ge layer and responsivity and surface reflectivity, respectively. The thickness (r) of the intrinsic Ge layer is ~ 800 nm, based on the secondary ion mass spectroscopy (SIMS)

results (not shown here). As the fiber is in contact with the SiO_2 passivation layer on the top of

FIG. 3. (a) Current–voltage curve of suspended germanium membranes photodetectors under dark and light conditions at point 1 and 2; (b) Experimental responsivities with varying wavelength with the detector region from central to edge (point 1 to point 4); (c) Extracted absorption spectral from 1,500 to 1,630 nm.

the photodiode during the photocurrent measurements, the light could be considered propagating in silica/ SiO_2 layers before reaching the Ge layer. Thus, by assuming the interface between the SiO_2 layer and the tip of the

fiber is lossless, surface reflectivity (r) could be calculated by the Fresnel relation: $r = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2$, where n_1 and n_2 are the refractivity of SiO_2 and Ge, respectively.²¹ Fig. 3(c) represents the extracted α between 1,500 to 1,630 nm of point 1 and 4 as compared to the bulk Ge. Compared to the α of 702 cm^{-1} at 1,630 nm, the α of $2,951 \text{ cm}^{-1}$ in the central region is enhanced by $\sim 4.2\times$ due to the strain amplification. This absorption coefficient is comparable with that of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ material at the same wavelength.²⁷ This result indicates Ge photodetectors could achieve a similar optoelectronic performance as III-V-dominated detectors in the field of short-wave infrared imaging. Furthermore, the $4.2\times$ absorption coefficient also indicates a $\sim 76\%$ decreased photon penetration depth ($\propto 1/\alpha$) in Ge, which could alleviate the typical trade-off between the responsivity and bandwidth.

We report a tunable biaxial tensile strain Ge photodetector on optical GeOI substrates fabricated by the CMOS compatible process. Tunable biaxial tensile strain of $\sim 0.22\text{--}1.01\%$ was achieved in the Ge membrane confirmed by FEM simulations and micro-Raman measurements. The extracted Ge absorption coefficient is enhanced by $\sim 4.2\times$ to $2,951 \text{ cm}^{-1}$ at 1,630 nm. Furthermore, due to the variable strain on the Ge mesa, each photodetector has the location-determined wavelength-selective photoresponsivity characteristics. This work offers a promising approach for adjusting the absorption spectra of the photodetector by applying geometrically amplified biaxial strain.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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