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Supplemental Information for

Intrinsic rippling enhances static non-reciprocity in a graphene metamaterial

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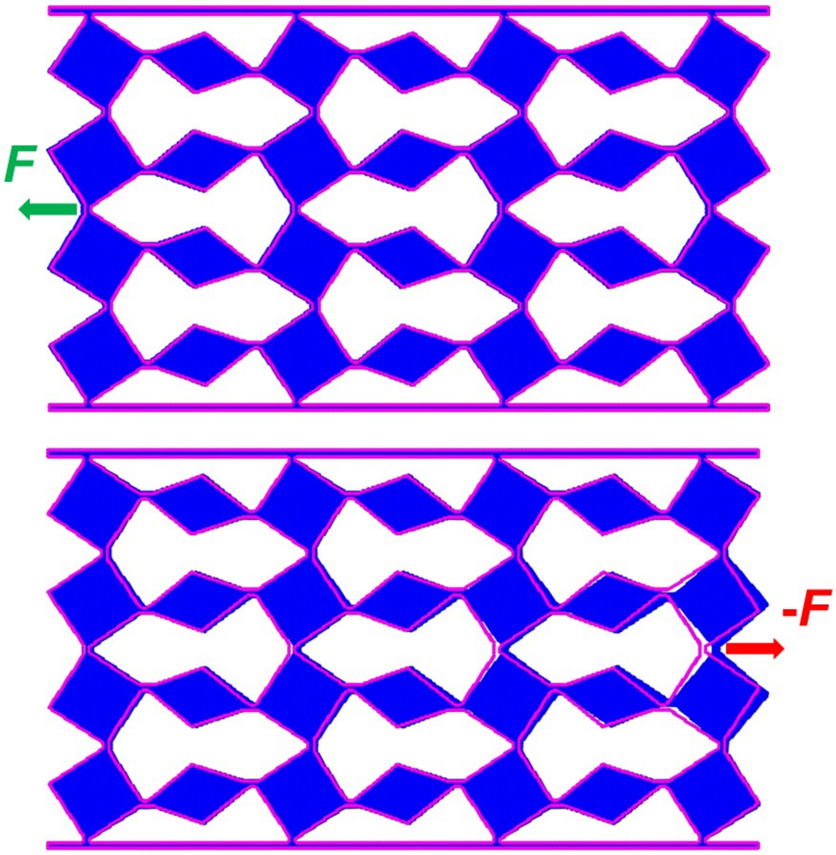

Figure S1: Mechanical response of the planar graphene metamaterials obtained by 2D MS with the angle $\theta = \pi/16$ when a force of -1.4 eV/Å is applied to the left end (top), and a force of 1.4 eV/Å is applied to the right end (bottom). The red solid lines indicate the configuration of the graphene metamaterial at unloaded state.

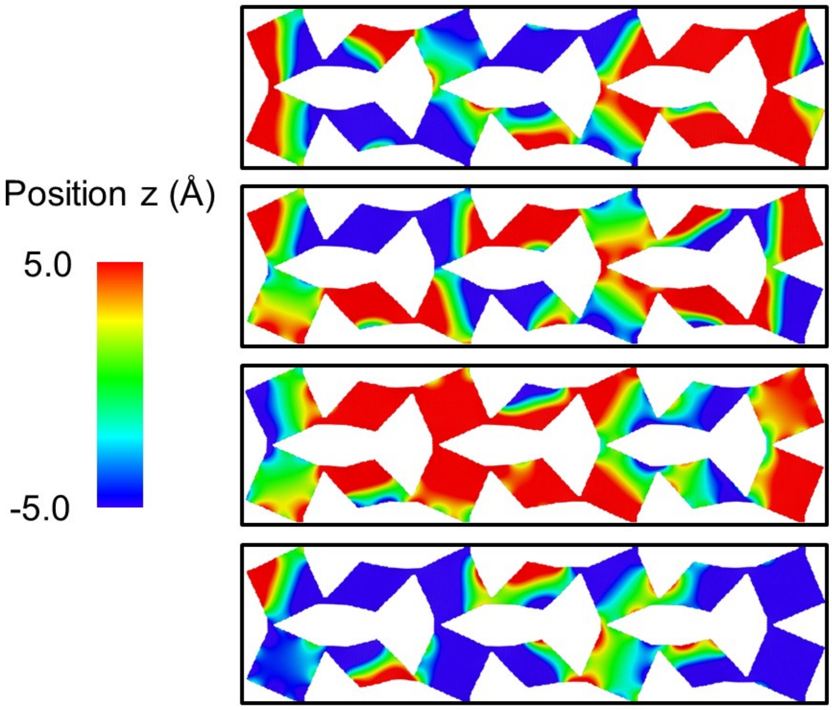

Figure S2: Rippling in the graphene metamaterials obtained by perturbed MS simulations. Stochastic behavior of graphene metamaterial for asymmetry angle $\pi/8$, for four different initial random displacement perturbations. Only the center two rows of the graphene metamaterial is shown.

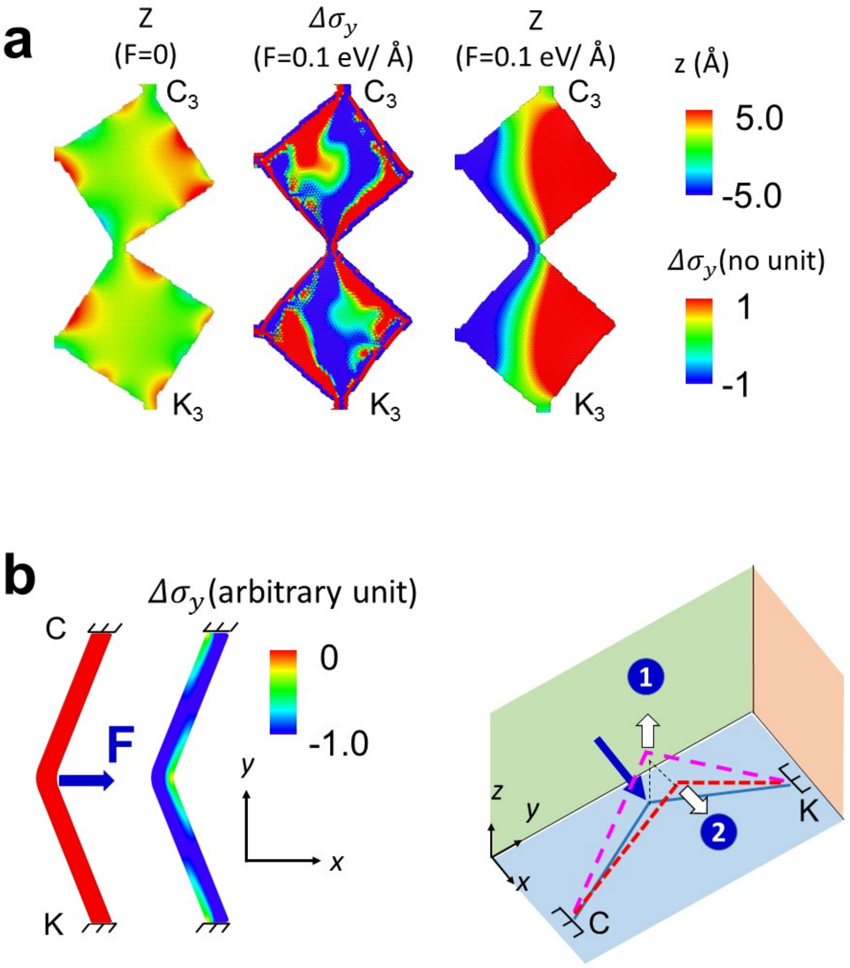

Figure S3: Rippling enhancement mechanism in the graphene metamaterial. (a): The stress field $\Delta\sigma_y$ and configuration of the two center rows squares in the rightmost column of the graphene metamaterial with the asymmetry angle of $\theta = \pi/16$ at unloaded state and when pulling at the left end with the force of 0.10 eV/Å. (b): Connected bars under loading. The two center squares in (a) can be regarded as two thin bars that are connected via a hinge. Compressive stress is generated in the bars. As a result, the connected bars response to the applied force with the two-step deformation mechanism. In the first step, the generated compressive stress in the y-direction, which causes the out-of-plane buckling of the bars due to the low bending modulus of the bars, increases the ripples' height (b). Now, the bars experience 3D movement rather than 2D movement so that the displacement of the bars depends on not only the in-plane stiffness but also the out-of-plane stiffness. It is noted that the stiffness of the bars becomes much smaller due to the low out-of-plane stiffness. Therefore, in the 3D displacement, the hinge can move to the right easily since the bars do not need to compress largely. If there are no ripples i.e., the bars experience 2D movement, it requires a large force to displace the hinge to the right because the displacement only depends on the in-plane stiffness, which is very large. In short, the increase of ripples' height due to the compressive stress fields enables large rotation of the bars about CK.

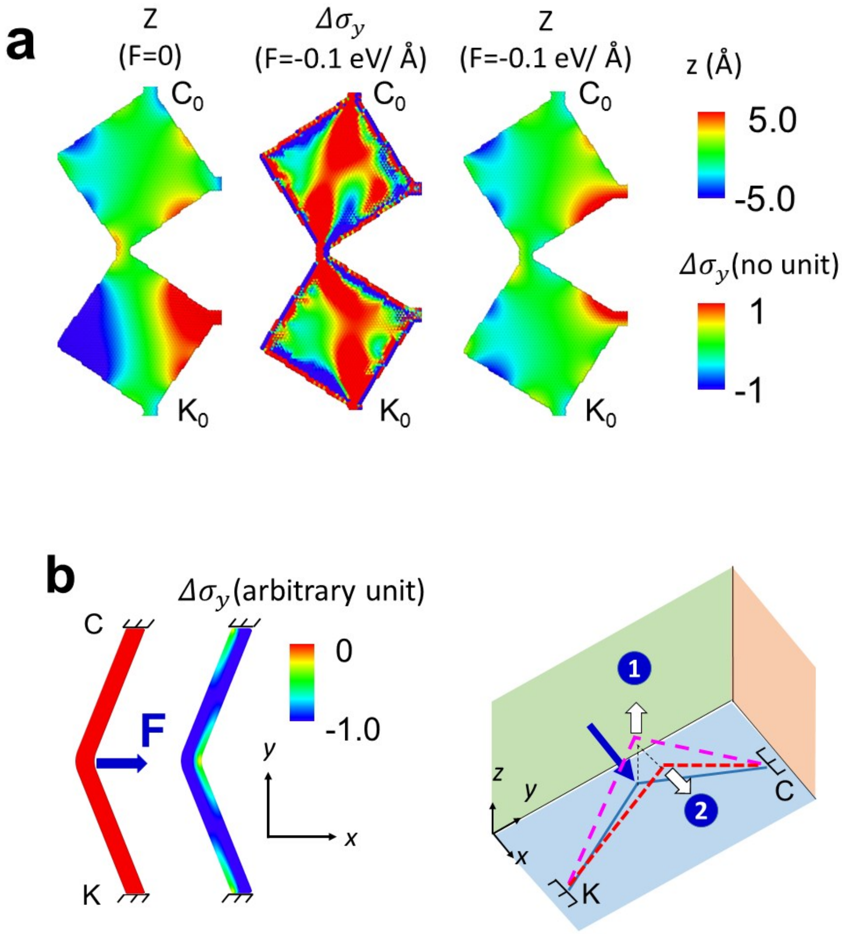

Figure S4: Rippling reduction mechanism in graphene metamaterial. (a): The stress field $\Delta\sigma_y$ and configuration of the rightmost column center-squares of the graphene metamaterial with the asymmetry angle of $\theta = \pi/16$ at unloaded state and when pulling at the left end with the force of -0.10 eV/Å. (b): Connected bars under loading. Two center squares in (a) can be regarded as two bars that connected via a hinge. The tensile stress is generated in the bars. As a result, the bars are simply stretched without any rotation.

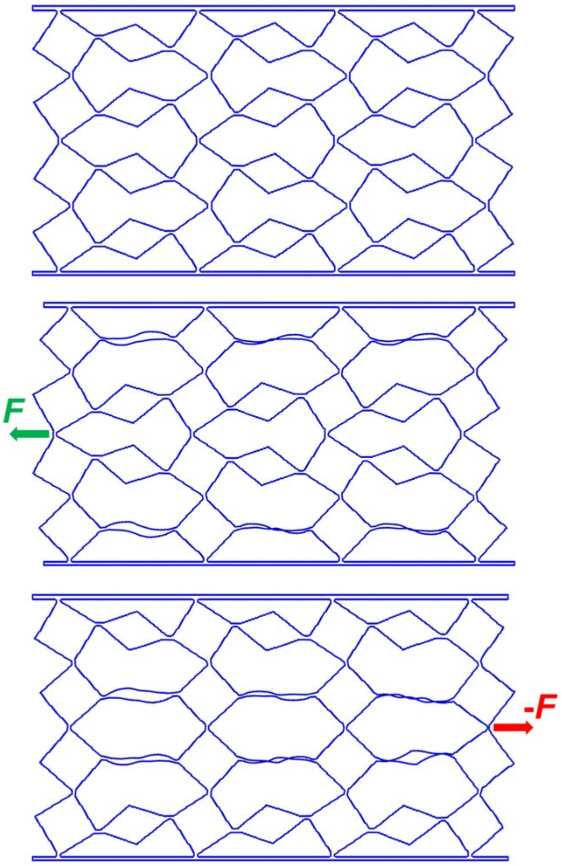

Figure S5: Atomic configurations of the ripped graphene metamaterials obtained by 3D MS simulations with the asymmetry angle $\theta = \pi/16$ when the metamaterial is at unloaded state (top), when a force of -0.7 eV/Å is applied to the left end (middle), and a force of 0.7 eV/Å is applied to the right end (bottom). Only atoms with a potential energy larger than 98% of the potential energy of the C atom of perfect graphene are shown, resulting only in the selected visualization of atoms at edges. This indicates that neither defect-mediated deformation nor fracture is observed in the metamaterial in the applied force range though the ligaments are under large rotation as well as out-of-plane buckling.