CLAIMS

~~What is claimed is:~~

1. A device comprising:

a substrate; and

a photodetector coupled to the substrate,

wherein the substrate has a depth in a depth direction,

wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device,

wherein the depth of the substrate is at most 1 times a diffusion length of a minority carrier within the substrate so as to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source; and

an additional photodetector coupled to the substrate,

wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.

~~wherein the substrate comprises surface defects on a second surface of the substrate, and~~

~~wherein the surface defects allow for recombination of electrons and holes so as to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.~~

~~2. The device of claim 1, wherein at least one of the surface defects comprises a topological defect, a defect where a translation symmetry of the second surface is broken, an adsorbate, an interface with another material, an inconsistent grain boundary, a stacking fault, an antiphase boundary, or a dangling bond.~~

~~3. The device of claims 1 or 2, further comprising an additional photodetector coupled to the substrate,~~

~~wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.~~

4. A device comprising:

a substrate; and

a photodetector coupled to the substrate,

wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device, and

wherein the substrate comprises crystallographic defects that allow for recombination of electrons and holes so as to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

5. The device of claim 4, further comprising an additional photodetector coupled to the substrate,

wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.

6. The device of claims 4 or 5, wherein the crystallographic defects comprise vacancy defects, interstitial defects, Frenkel defects, antisite defects, substitutional defects, or topological defects.

7. A device comprising:

a substrate; and

a photodetector coupled to the substrate,

wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device, and

wherein a depth of the substrate is at most 100 times a diffusion length of a minority carrier within the substrate so as to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

8. The device of claim 7, further comprising an additional photodetector coupled to the substrate,

wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.

~~9~~2. The device of ~~claims 7 or 8~~claim 1, wherein the depth of the substrate is ~~at most 10 times the diffusion length of the minority carrier within the substrate, at most 1 times the diffusion length of the minority carrier within the substrate,~~ at most 0.1 times the diffusion length of the minority carrier within the substrate~~, or at most 0.01 times the diffusion length of the minority carrier within the substrate~~.

~~10. The device of any of claims 7-9, wherein the depth of the substrate is at most 1000 times an optical absorption length of the substrate, at most 100 times the optical absorption length of the substrate, at most 10 times the optical absorption length of the substrate, at most the optical absorption length of the substrate, at most 0.1 times the optical absorption length of the substrate, at most 0.01 times the optical absorption length of the substrate, or at most 10^{-3} times the optical absorption length of the substrate.~~

3. The device of claim 1, wherein the depth of the substrate is at most an optical absorption length of the substrate.

~~11~~4. The device of ~~any of claims 7-10~~claim 1, wherein the depth of the substrate defines a maximum absorption depth for the light emitted from the light source.

~~12~~5. A device comprising:

a substrate; and

a photodetector coupled to the substrate,

wherein the substrate has a depth in a depth direction,

wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device, and

wherein the depth of the substrate is at most 1 times a diffusion length of a minority carrier within the substrate so as to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

~~wherein the device has a band structure based on a material composition of the substrate and the photodetector, and~~

~~wherein the band structure is configured to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.~~

~~13~~6. The device of claim ~~12~~5, further comprising an additional photodetector coupled to the substrate,

wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates ~~a~~the top surface of the device and is electrically connected in series with the photodetector~~, and~~

~~wherein the band structure is based on a material composition of the additional photodetector~~.

7. The device of claim 5, wherein the depth of the substrate is at most 0.1 times the diffusion length of the minority carrier within the substrate.

8. The device of claim 5, wherein the depth of the substrate is at most an optical absorption length of the substrate.

9. The device of claim 5, wherein the depth of the substrate defines a maximum absorption depth for the light emitted from the light source.

~~14. The device of claims 12 or 13,~~

~~wherein the band structure induces an electric field that extends beyond a depletion region of the photodetector based on a curvature of a conduction band or a valence band of the band structure beyond the depletion region of the photodetector, and~~

~~wherein the electric field is configured to induce a drift current that accelerates minority carriers toward the depletion region of the photodetector when minority carriers are photoexcited in the substrate based on the light emitted from the light source.~~

~~15. The device of any of claims 12-14,~~

~~wherein the band structure comprises a potential barrier, and~~

~~wherein the potential barrier is configured to prevent minority carriers photoexcited in the substrate from reaching a depletion region of the photodetector due to diffusion.~~

~~16. The device of claim 15, wherein a barrier thickness corresponding with the potential barrier is at least 1 nm thick, at least 10 nm thick, or at least 100 nm thick.~~

~~17. The device of claims 15 or 16,~~

~~wherein the substrate comprises a band gap,~~

~~wherein the potential barrier comprises a conduction band energy that is at least 0.01 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.05 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.1 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.15 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.2 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.25 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.5 times the band gap of the substrate above the conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.75 times the band gap of the substrate above the conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 1.0 times the band gap of the substrate above the conduction band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.01 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.05 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.1 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.15 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.2 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.25 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.5 times the band gap of the substrate above the valence band energy of the band structure of the substrate~~

surrounding the potential barrier, a valence band energy that is at least 0.75 times the band gap of the substrate above the valence band energy of the band structure of the substrate surrounding the potential barrier, or a valence band energy that is at least 1.0 times the band gap of the substrate above the valence band energy of the band structure of the substrate surrounding the potential barrier.

18. The device of any of claims 12-17,

wherein the band structure comprises a potential well, and

wherein the potential well is configured to prevent minority carriers photoexcited in the substrate from reaching a depletion region of the photodetector due to diffusion.

19. The device of claim 18, wherein a well thickness corresponding to the potential well is at least 1 nm thick, at least 10 nm thick, or at least 100 nm thick.

20. The device of claims 18 or 19,

wherein the substrate comprises a band gap,

wherein the potential well comprises a conduction band energy that is at least 0.01 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.05 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.1 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.15 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.2 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.25 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.5 times the band gap of the substrate below the conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.75 times the band gap of the substrate below the conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 1.0 times the band gap of the substrate below the conduction band energy of the band structure of

~~the substrate surrounding the potential well, a valence band energy that is at least 0.01 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.05 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.1 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.15 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.2 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.25 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.5 times the band gap of the substrate below the valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.75 times the band gap of the substrate below the valence band energy of the band structure of the substrate surrounding the potential well, or a valence band energy that is at least 1.0 times the band gap of the substrate below the valence band energy of the band structure of the substrate surrounding the potential well.~~

~~21. The device of any of claims 12-20,~~

~~wherein the substrate comprises two or more materials,~~

~~wherein the band structure comprises a heterostructure,~~

~~wherein the heterostructure comprises a first material with a band gap larger than a photon energy associated with the light emitted from the light source, and~~

~~wherein the first material is present within the substrate at a first depth within the substrate to define a maximum absorption depth for the light emitted from the light source.~~

~~22. A device comprising:~~

~~a substrate; and~~

~~a photodetector coupled to the substrate,~~

~~wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device; and~~

~~an anti-reflective layer coupled to a second surface of the substrate,~~

~~wherein the anti-reflective layer is configured to couple light passing through the~~

substrate to an exterior of the device, thereby preventing reflections within the substrate of the light emitted from the light source so as to reduce minority carrier photoexcitation in the substrate based on the light emitted from the light source, so as to mitigate dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

23. The device of claim 22, further comprising an additional photodetector coupled to the substrate,

wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.

24. The device of claims 22 or 23, wherein the anti-reflective layer comprises a graded-index anti-reflective coating, a quarter-wave optical layer, a Bragg grating, a diffraction grating, or an index-matched, passive substrate.

25. A device comprising:

a substrate; and

a photodetector coupled to the substrate,

wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device,

wherein a second surface of the substrate is polished or planarized, thereby preventing reflections within the substrate of the light emitted from the light source so as to reduce minority carrier photoexcitation in the substrate based on the light emitted from the light source, thereby mitigating dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

26. The device of claim 25, further comprising an additional photodetector coupled to the substrate,

wherein the additional photodetector coupled to the substrate is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.

~~27. A device comprising:~~

~~a substrate;~~

~~a photodetector coupled to the substrate; and~~

~~a band-reject optical filter,~~

~~wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device,~~

~~wherein light from the light source that irradiates the top surface of the device is transmitted through the band-reject optical filter, and~~

~~wherein the band-reject optical filter is configured to reduce intensity of one or more wavelengths of the light emitted from the light source, so as to reduce minority carrier photoexcitation in the substrate based on the light emitted from the light source, thereby mitigating dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.~~

~~28. The device of claim 27, further comprising an additional photodetector coupled to the substrate,~~

~~wherein the additional photodetector coupled to the substrate is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.~~

~~29. A device comprising:~~

~~a substrate;~~

~~a photodetector coupled to the substrate; and~~

~~a non-linear optical absorber,~~

~~wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device,~~

~~wherein light from the light source that irradiates the top surface of the device is transmitted through the non-linear optical absorber, and~~

~~wherein the non-linear optical absorber is configured to reduce intensity of one or more wavelengths of the light emitted from the light source that are at or above a threshold power level, so as to reduce minority carrier photoexcitation in the substrate based on the light emitted from the light source, thereby mitigating dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.~~

30. The device of claim 29, further comprising an additional photodetector coupled to the substrate,

wherein the additional photodetector coupled to the substrate is arranged to detect light emitted from the light source that irradiates the top surface of the device and is electrically connected in series with the photodetector.

31. A method comprising:

providing a device comprising:

a substrate; and

a photodetector coupled to the substrate,

wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the device;

providing light from the light source; and

mitigating dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

32. The method of claim 31, wherein mitigating the dark current comprises providing light from the light source such that the light from the light source irradiates a bottom surface of the device.

33. The method of claims 31 or 32, wherein mitigating the dark current comprises modifying an operating temperature of the device.

34. The method of any of claims 31-33, wherein mitigating the dark current comprises modulating a wavelength of the light emitted from the light source.

35. The method of any of claims 31-34, wherein mitigating the dark current comprises modulating a power of the light emitted from the light source.

36. The method of any of claims 31-35, wherein mitigating the dark current comprises modulating a pulse frequency or duty cycle of the light emitted from the light source.

37. A method of manufacture comprising:

providing a substrate;

forming a photodetector within or on the substrate, wherein the photodetector is arranged to detect light emitted from a light source that irradiates a top surface of the photodetector; and

performing a processing step that mitigates dark current arising from minority carriers photoexcited in the substrate based on the light emitted from the light source.

38. The method of claim 37, wherein performing the processing step that mitigates dark current comprises thinning the substrate by removing a portion of the substrate, thereby reducing a depth of the substrate to less than or equal to 100 times a diffusion length of a minority carrier within the substrate.

39. The method of claims 37 or 38, wherein performing the processing step that mitigates dark current comprises producing crystallographic defects within the substrate that allow for recombination of electrons and holes.

40. The method of any of claims 37-39, wherein performing the processing step that mitigates dark current comprises defining a band structure based on a material composition of the substrate and the photodetector.

41. The method of claim 40,

wherein the band structure induces an electric field that extends beyond a depletion region of the photodetector based on a curvature of a conduction band or a valence band of the band structure beyond the depletion region of the photodetector, and

wherein the electric field is configured to induce a drift current that accelerates minority carriers toward the depletion region of the photodetector when minority carriers are photoexcited in the substrate based on the light emitted from the light source.

42. The method of claims 40 or 41,

wherein the band structure comprises a potential barrier, and

wherein the potential barrier is configured to prevent minority carriers photoexcited in the substrate from reaching a depletion region of the photodetector due to diffusion.

43. The method of claim 42, wherein a barrier thickness corresponding to the potential barrier is at least 1 nm thick, at least 10 nm thick, or at least 100 nm thick.

44. The method of claims 42 or 43,

wherein the substrate comprises a band gap,

wherein the potential barrier comprises a conduction band energy that is at least 0.01 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.05 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.1 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.15 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.2 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.25 times the band gap of the substrate above a conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.5 times the band gap of the substrate above the conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 0.75 times the band gap of the substrate above the conduction band energy of the band structure of the substrate surrounding the potential barrier, a conduction band energy that is at least 1.0 times the band gap of the substrate above the conduction band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.01 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.05 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.1 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.15 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.2 times the band gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.25 times the band

~~gap of the substrate above a valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.5 times the band gap of the substrate above the valence band energy of the band structure of the substrate surrounding the potential barrier, a valence band energy that is at least 0.75 times the band gap of the substrate above the valence band energy of the band structure of the substrate surrounding the potential barrier, or a valence band energy that is at least 1.0 times the band gap of the substrate above the valence band energy of the band structure of the substrate surrounding the potential barrier.~~

~~45. The method of any of claims 40-44,~~

~~wherein the band structure comprises a potential well, and~~

~~wherein the potential well is configured to prevent minority carriers photoexcited in the substrate from reaching a depletion region of the photodetector due to diffusion.~~

~~46. The method of claim 45, wherein a well thickness corresponding to the potential well is at least 1 nm thick, at least 10 nm thick, or at least 100 nm thick.~~

~~47. The method of claims 45 or 46,~~

~~wherein the substrate comprises a band gap,~~

~~wherein the potential well comprises a conduction band energy that is at least 0.01 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.05 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.1 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.15 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.2 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.25 times the band gap of the substrate below a conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.5 times the band gap of the substrate below the conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 0.75~~

~~times the band gap of the substrate below the conduction band energy of the band structure of the substrate surrounding the potential well, a conduction band energy that is at least 1.0 times the band gap of the substrate below the conduction band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.01 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.05 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.1 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.15 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.2 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.25 times the band gap of the substrate below a valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.5 times the band gap of the substrate below the valence band energy of the band structure of the substrate surrounding the potential well, a valence band energy that is at least 0.75 times the band gap of the substrate below the valence band energy of the band structure of the substrate surrounding the potential well, or a valence band energy that is at least 1.0 times the band gap of the substrate below the valence band energy of the band structure of the substrate surrounding the potential well.~~

~~48. The method of any of claims 40-47,~~

~~wherein the substrate comprises two or more materials,~~

~~wherein the band structure comprises a heterostructure,~~

~~wherein the heterostructure comprises a first material with a band gap larger than a photon energy associated with the light emitted from the light source, and~~

~~wherein the first material is present within the substrate at a first depth within the substrate to define a maximum absorption depth for the light emitted from the light source.~~

~~49. The method of any of claims 37-48, wherein performing the processing step that mitigates dark current comprises coupling an anti-reflective layer to a second surface of the substrate, and~~

~~wherein the anti-reflective layer is configured to couple light passing through the~~

~~substrate to an exterior of the substrate, thereby preventing reflections within the substrate of the light emitted from the light source so as to reduce photoexcitation of minority carriers within the substrate.~~

~~50. The method of claim 49, wherein the anti-reflective layer comprises a graded-index anti-reflective coating, a quarter-wave optical layer, a Bragg grating, a diffraction grating, or an index-matched, passive substrate.~~

~~51. The method of any of claims 37-50, wherein performing the processing step that mitigates dark current comprises polishing or planarizing a second surface of the substrate, thereby preventing reflections within the substrate of the light emitted from the light source so as to reduce photoexcitation of minority carriers within the substrate.~~

~~52. The method of any of claims 37-51, wherein performing the processing step that mitigates dark current comprises applying a band-reject optical filter over the top surface of the photodetector, thereby configuring the photodetector such that light emitted from the light source irradiates the photodetector through the band-reject optical filter, and~~

~~wherein the band-reject optical filter is configured to reduce intensity of one or more wavelengths of the light emitted from the light source, so as to reduce photoexcitation of minority carriers in the substrate based on the light emitted from the light source.~~

~~53. The method of any of claims 37-52, further comprising flip-chip bonding the substrate and the photodetector to one or more electrodes used to bias the photodetector such that the photodetector is arranged to detect light from the light source that irradiates a second surface of the substrate.~~

~~54. The method of any of claims 37-53, further comprising:~~

~~forming an additional photodetector within or on the substrate, wherein the additional photodetector is arranged to detect light emitted from the light source that irradiates a top surface of the additional photodetector; and~~

~~electrically connecting the additional photodetector in series with the photodetector.~~

~~55. The method of any of claims 37-54, wherein one or more regions of the photodetector or the substrate are defined using lithography.~~