APAM 2D bipolar device fabrication

J. H. G. Owen, R. Santini, E. Fuchs and J. N. Randall
Zyvex Labs LLC, 1301 N. Plano Rd, Richardson, TX 75081, USA.

We are creating 2D Bipolar devices using Atomic Precision Advanced Manufacturing (APAM)[1], the ability to fabricate 2D atomic-scale devices such as the 'single-atom transistor' [2] and dopant patch array devices [3] via the placement of *n*-type dopants such as P and As and *p*-type dopants such as B and Al [4] in single planes of Si(001).

We have developed a new sample design optimized for device fabrication, shown in Fig. 1. Trenches are etched into the wafer, for two purposes. First, they are visible in the STM camera, allowing for rapid location of the device area. Second, the trenches block step flow across the surface during sample preparation, producing a device area with large terraces, which is preferential for atomic-scale writing. Using alignment marks etched into the wafer along with the trenches, masks for post-processing can be aligned to the device areas, allowing for metal electrodes to connect the buried device pattern to the outside world.

The atomic-scale fabrication process involves atomic-precision patterning using H Depassivation Lithography, followed by dosing of the dopant precursor, and an incorporation anneal. For bipolar devices, the P parts of the device are patterned, dosed with PH_3 and incorporated first, then the surface is repassivated, and a second round of patterning is performed for the B parts, using BCl_3. The second round of patterning must be aligned with atomic precision to the P parts as shown in Fig.2. Finally, the complete device is buried in 20-30 nm of epitaxial Si [1].

(1) Bussmann, E. *et al.* Atomic - Precision Advanced Manufacturing for Si Quantum Computing. *MRS Bull.* **2021**, *46*, 1–9.
(2) Fuechsle, M. *et al.* A Single-Atom Transistor. *Nat Nano* **2012**, *7*, 242–246.
(3) Wang, X. *et al.* Atomic-Scale Control of Tunneling in Donor-Based Devices. *Commun. Phys.* **2020**, *3*, 82.
(4) Dwyer, K. J. *et al.* Area-selective deposition and B delta-doping of Si(100) with BCl_3; Radue, M. S. *et al.* $AlCl_3$-Dosed Si(100)-2x1: Adsorbates, Chlorinated Al Chains, and Incorporated Al. arxiv **(2021).**
(5) Škereň, T. *et al.* Bipolar Device Fabrication Using a Scanning Tunnelling Microscope. *Nat. Electron.* **2020**, *3*, 524–530.

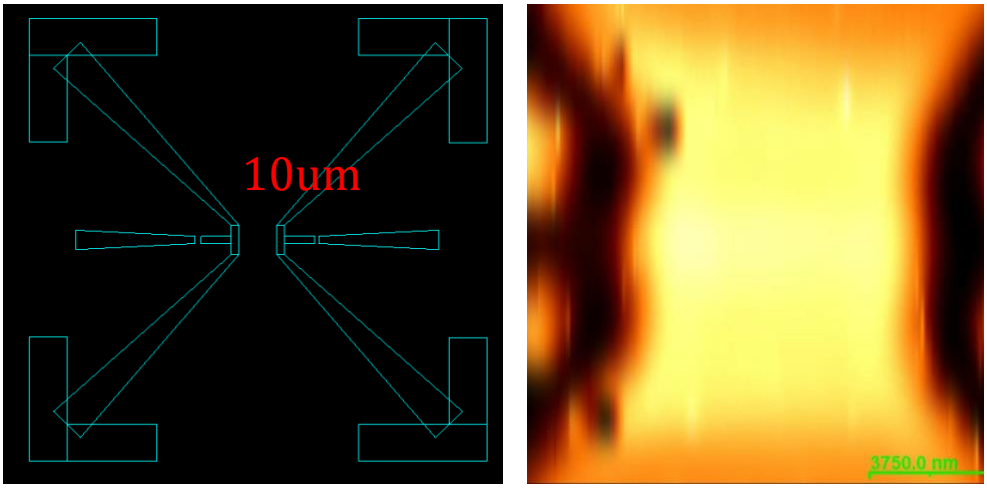

Fig. 1: (left): CAD drawing of device pattern. (Right): STM image of central device area. The device area was located at the first attempt using the STM camera view.

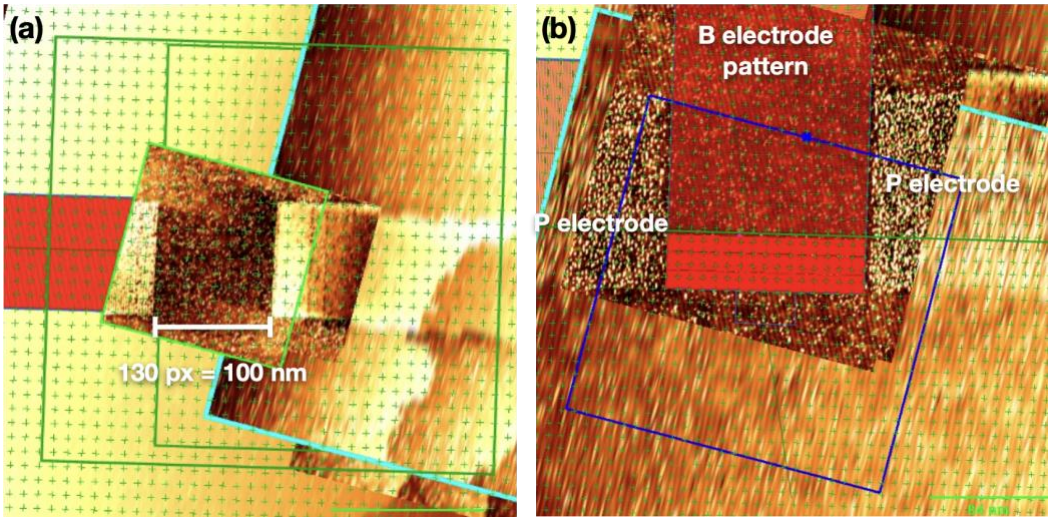

Fig. 2: (a): P electrodes with 130 px, (100 nm) spacing. (b) B electrode pattern aligned precisely between completed P electrodes.