

## Electronic Supplementary Materials

for

### Predicting Human Touch Sensitivity to Single Atom Substitutions in Surface Monolayers for Molecular Control in Tactile Interfaces

Abigail Nolin<sup>1</sup>, Amanda Licht<sup>1</sup>, Kelly Pierson<sup>1</sup>, Chun-Yuan Lo<sup>2</sup>, Laure V. Kayser<sup>1,2</sup>, Charles Dhong<sup>1,3\*</sup>

<sup>1</sup>Department of Materials Science & Engineering, University of Delaware, Newark, DE 19716, USA

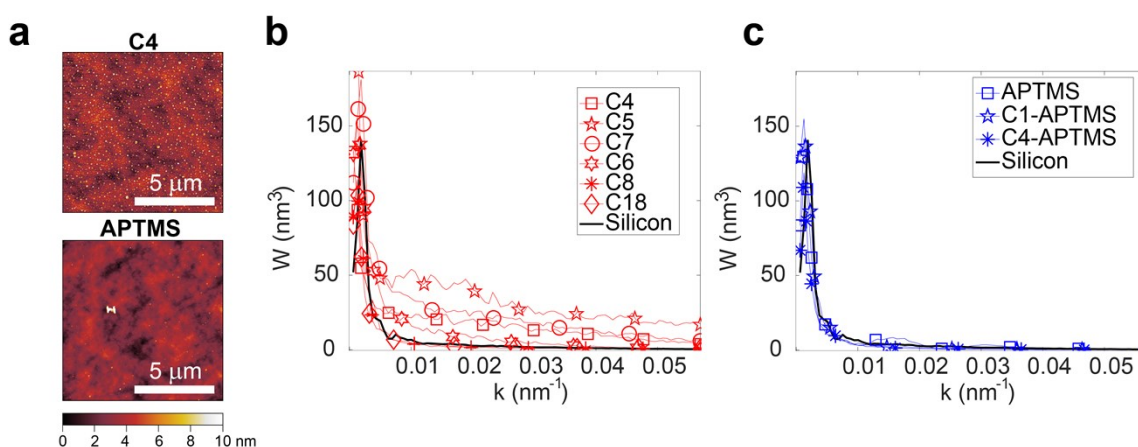
<sup>2</sup>Department of Chemistry and Biochemistry, University of Delaware, Newark, DE 19716, USA

<sup>3</sup>Department of Biomedical Engineering, University of Delaware, Newark, DE 19716, USA

\*Author to whom correspondence should be addressed: cdhong@udel.edu

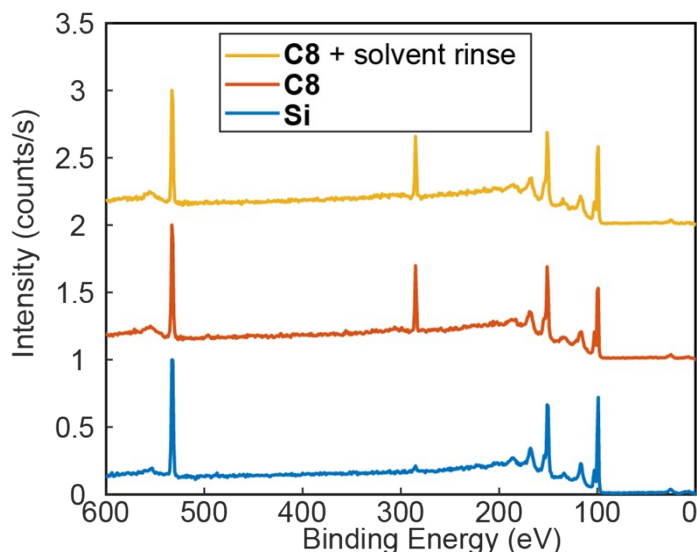
#### S1. Silane Characterization

*Atomic Force Microscopy.* Example of results are in **Figure S1a**. Surfaces over a relatively large area show physisorbed aggregates, more prevalent in C4.<sup>1</sup> The power spectral densities (PSD)<sup>2</sup> of the alkylsilanes in **Figure S2b** and aminosilanes in **Figure S2c** indicate a more disordered surface in alkylsilanes below a length of C8. The PSD of C8 and C18 appear more like the bare silicon control. C6 appears to show less disorder than C7, potentially due to less efficient chain packing off odd-length chains.<sup>3</sup>



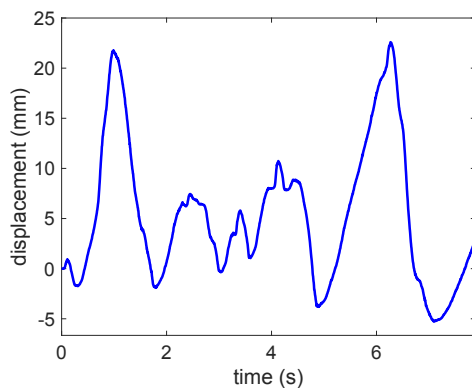
**Figure S1. Surface profiles by atomic force microscopy.** (a) Surface profiles of C4 and APTMS. Scan area of  $10\ \mu\text{m} \times 10\ \mu\text{m}$ . (b) Power spectral density (PSD) of surfaces of alkylsilanes to characterize roughness. (c) PSD of aminosilanes.

*X-ray photoelectron spectroscopy.* XPS was performed on silanized silicon substrates to determine the chemical bonding on the surface after the silanization reaction. To confirm chemical bonding of the silane, instead of physical adsorption, we performed an ethanol rinse and sonication as detailed by Yang et al.<sup>4</sup> to remove any excess species. XPS of the as-prepared surfaces and ethanol rinse/sonicated surfaces are shown in **Figure S2**. The similarity in between the as prepared samples and ethanol rinse/sonicated samples indicates that the prepared samples did not have any significant physisorbed species and the silanes were chemically bound to the surface.



**Figure S2. Surface profiles by atomic force microscopy.** XPS spectrum of bare silicon, C8, and C8 after the solvent rinse described by Yang et al.<sup>4</sup>.

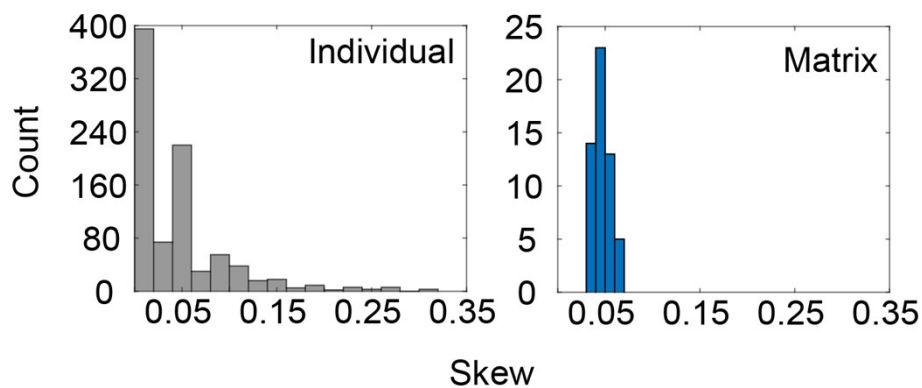
**S2. Human sliding velocity and applied mass.** For our mechanical tests, we used conditions largely consistent with other studies on fine touch. We asked subjects to slide their finger across samples while tracking their motion with a small ( $\sim 1\ \text{mm}$ ,  $< 5\ \text{g}$ ) motion capture device at 240 Hz and  $\sim 0.02\ \text{mm}$  accuracy (Polhemus Liberty Motion Tracking). (see **Figure S3**) Exploration velocities ranged from 13.5-42.8 mm/s. For applied mass, subjects were asked to slide their finger across a wafer on a scale. Applied masses ranged from 9.3 g to 93.8 g. Subjects indicated they were able to press harder but did not typically exceed 100 g for discrimination tasks.



**Figure S3. Motion tracking of subject finger.** Subject motion tracking data used to determine exploration velocity conditions in mechanical tests.

### **S3. Cross-correlation and skew analysis.**

The skew of the cross-correlation is normalized to have a maximum value of 1 based on all measurements simply for convenience in plotting and to highlight the concept that descriptive parameters (variance, kurtosis, etc.) of the cross-correlation are comparable through discriminability matrices. A distribution of skews is shown in **Figure S4**. On the left is the skew from each cross-correlation at each mass and velocity per comparison of pairs of silanes. On the right is the skew summed from all masses and velocities per comparison of pairs of silanes. The scale factor for skew used in the discriminability matrices is 3.17, which is evident from normalizing the maximum skew encountered in this experiment, which was 0.315. Normally, the sign of the skew indicates whether the skew is left or right. However, we took the absolute value of skew at under each experimental condition, so a single silane with large amounts of either left or right skew would result in a surface with overall high skew and that the conditions which generate left or right skew do not cancel each other out.



**Figure S4. Distribution of individual and aggregate skew.** Left, distribution of skew from each mass and velocity from all combinations of silanes, resulting in 16 counts per given combination of silane. Right, aggregate distribution of skew by summing all sixteen combinations of masses and velocity for a given combination of silanes.

#### **S4. Power analysis for number of subjects needed in human testing**

We estimated the number of subjects required for an odd-man-out (three-alternative forced choice) psychophysics through a power analysis. Previously, it was shown that humans can distinguish between perfluorooctyltrichlorosilane and plasma oxidized surfaces.<sup>5</sup> Upon inspection, the perfluorooctyltrichlorosilane and plasma oxidation generate surfaces with relatively large differences in structures and surface energy. Therefore, we assumed a lower average success rate 60% in our proposed tests, but a similar standard deviation of 15%. Given that chance is 33%, at a power of 0.95, the power analysis indicates that  $n=7$  subjects are necessary. However, assumed independence the task as a sequence of five Bernoulli trials, we exceeded the number required in power test by having each subject perform five trials.

*Human psychophysical testing.* Subjects were asked to perform an “odd-man-out” test. In an odd-man-out test, three samples are presented at the same time to a subject. Two of these samples are the same while the third sample has a different surface coating. The location of the different sample and the type of coating was randomized across trials and subjects. Subjects could freely explore the three samples and then asked

which sample was different from the other two. Typical exploration time for a comparison took 10-30 seconds.

## References

- 1 J. Li and J. H. Horton, *J. Mater. Chem.*, 2002, **12**, 1268–1273.
- 2 X. Cui, J. F. Hetke, J. A. Wiler, D. J. Anderson and D. C. Martin, *Sensors Actuators A Phys.*, 2001, **93**, 8–18.
- 3 Z. Wang, J. Chen, S. Oyola-Reynoso and M. Thuo, *Coatings*, 2015, **5**, 1034–1055.
- 4 Y. Yang, A. M. Bittner, S. Baldelli and K. Kern, *Thin Solid Films*, 2008, **516**, 3948–3956.
- 5 C. W. Carpenter, C. Dhong, N. B. Root, D. Rodriguez, E. E. Abdo, K. Skelil, M. A. Alkhadra, J. Ramírez, V. S. Ramachandran and D. J. Lipomi, *Mater. Horizons*, 2018, **5**, 70–77.