Supporting information

Voltage controlled hot carrier injection enables ohmic contacts using Au Island Metal Films on Ge.

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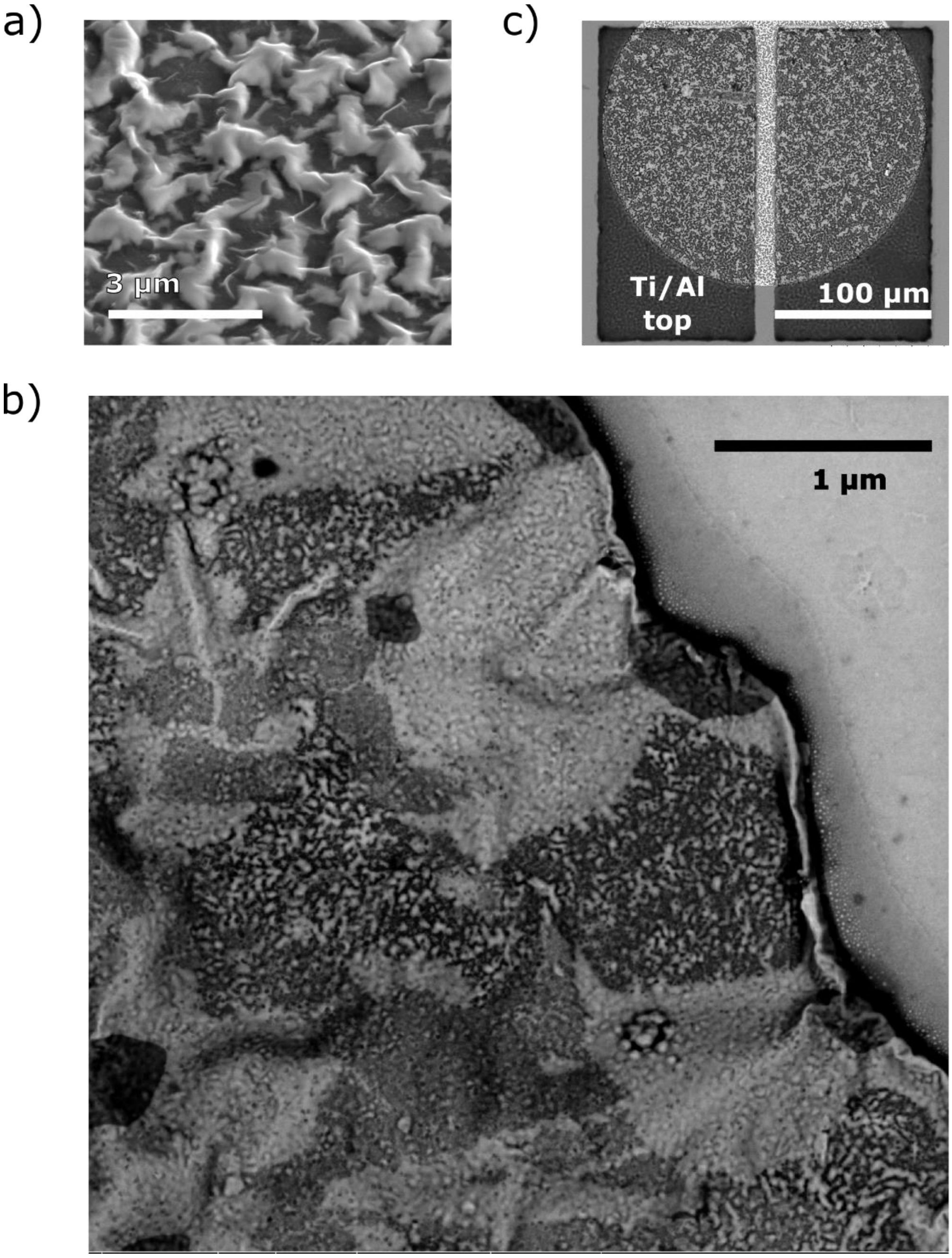

Figure S1: **HRSEM survey of IMFs a.** SEM image showing Island Metal Film network of nanowires and clusters (tilted view 53°). **b.** Low energy HRSEM of the patterned edge of the IMF, showing thermally driven self-organization of smaller islands between larger islands and evidence of film retraction which forms the nanowires. **c.** SEM image shows the patterned top metal used to probe a 10 µm region in the patterned IMF.

Island film formation and top contact metallization

High resolution SEM (HRSEM) images of the IMF in Fig.S1.a. and Fig. S1.b. show a detailed network of nanostructures. Fig. S1.b shows HRSEM of the IMF inside a circular patterned contact on Ge, imaged using low energy electron illumination. Smaller islands organize between larger clusters seen in Fig. S1.a. The patterned edge retracts during annealing and forms a continuous nanowire. Au nanodot (~ 2 nm) formations were observed in this region. A Ge rich (dark) layer can be seen close to the retracted nanowire edge, in agreement with selective evaporation of Ge from the Au/Ge eutectic reaction, reported in refs. 17 and 18. The initially planar film develops holes, which expand under compressive stress (Au/Cr) during accelerated annealing. All retracted edges have nano-island formations at their boundary. However, the annealing recipe needs to be carefully controlled in order to preserve the IMF arrangement. Long annealing schedules (> 1 min) results in complete imbedding of the nanostructures into the melted substrate and the hot carrier effect is lost.

Ti/Al (20:80) top contacts (100 nm thick) were fabricated as shown in Fig.S1.c (dark rectangular areas) to probe the IMF in array configuration for the electron emission experiment (Fig. 4, main text). The spacing between the top contacts is ~10 μm.

EFTEM showing the Cr migration in Au

Spatially resolved Energy filtered TEM (EFTEM) chemical maps of the IMF cross sections (unfiltered views) are shown, alongside their corresponding Chromium **L** signal maps, at the edge of a cluster in Fig. S2.a and at the patterned edge of the contact (nanowire) in Fig. S2.b. Cr signal maps (bright pixels) indicate diffusion through Au, which results in encapsulation of the Au nanostructures. These results explain why Cr signal were observed in SEM/ EDX measurements taken during the materials investigation. Compressive stress continues to fold

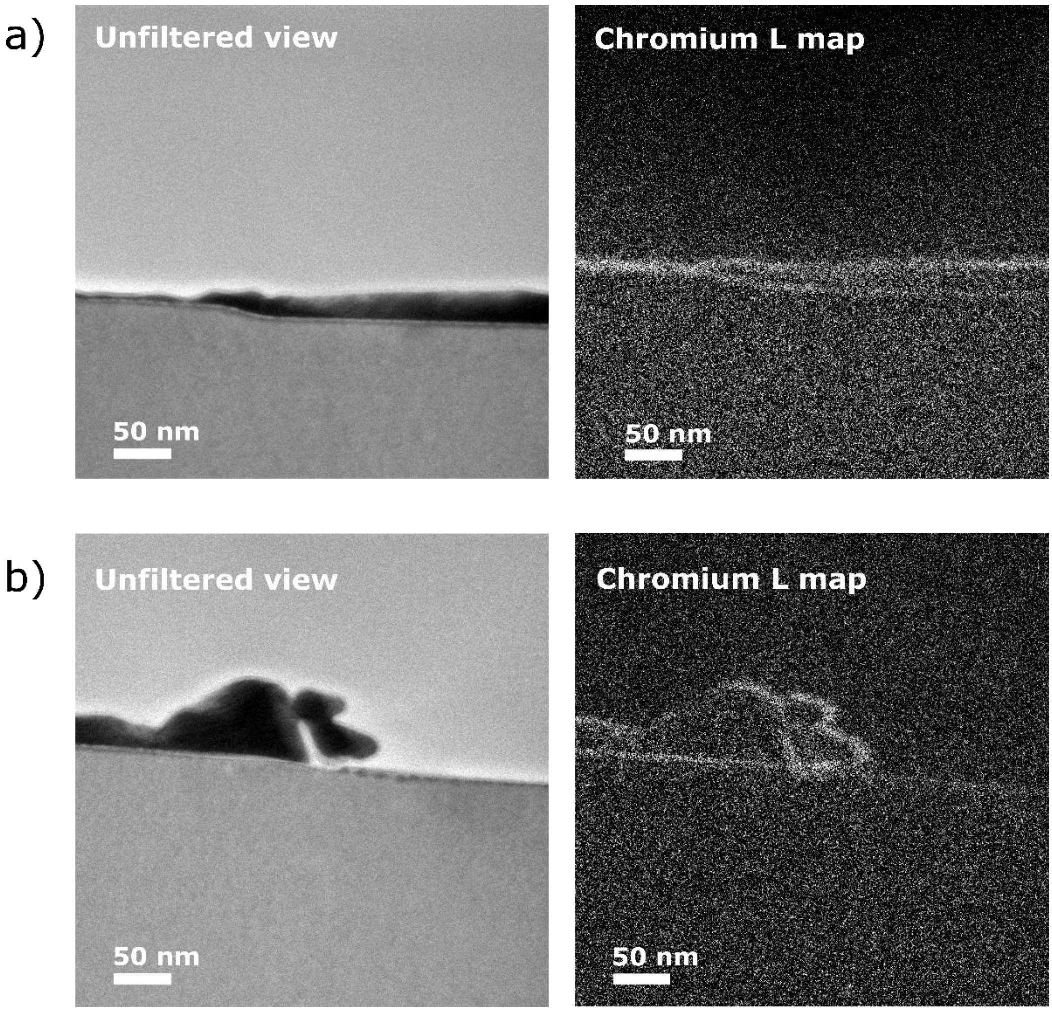

Figure S2: **Cr encapsulation of Au nanostructures. a.** EFTEM of an Au island alongside its Chromium L map. **b.** EFTEM of an Au nanowire, alongside its Chromium L map.

the nanowire at the diffused Cr/Au surface to form a cantilever like structure. The Cr diffusion is very quick and cannot be stopped. The original interface is however seen preserved, acting as a barrier layer to the substrate. Therefore, interfaces remain nominally flat as long as the Cr layer does not crack under thermal stress.

Orientation relationships between Au and Ge

EBSD analysis (Fig. S3.a) of the annealed 100/5 nm Au/Cr (IMF) shows multi-variant <110>Au//[100]Ge and {001}Au//{011}Ge orientation relationships between Au and Ge, as illustrated using schematic unit cells. In contrast, the 300/5 nm Au/Cr (CMF) showed no clear texture. Fig. S3.b shows the (620)Ge plane phi-scan to reference substrate contributions observed in Fig. 3.d in the main text.

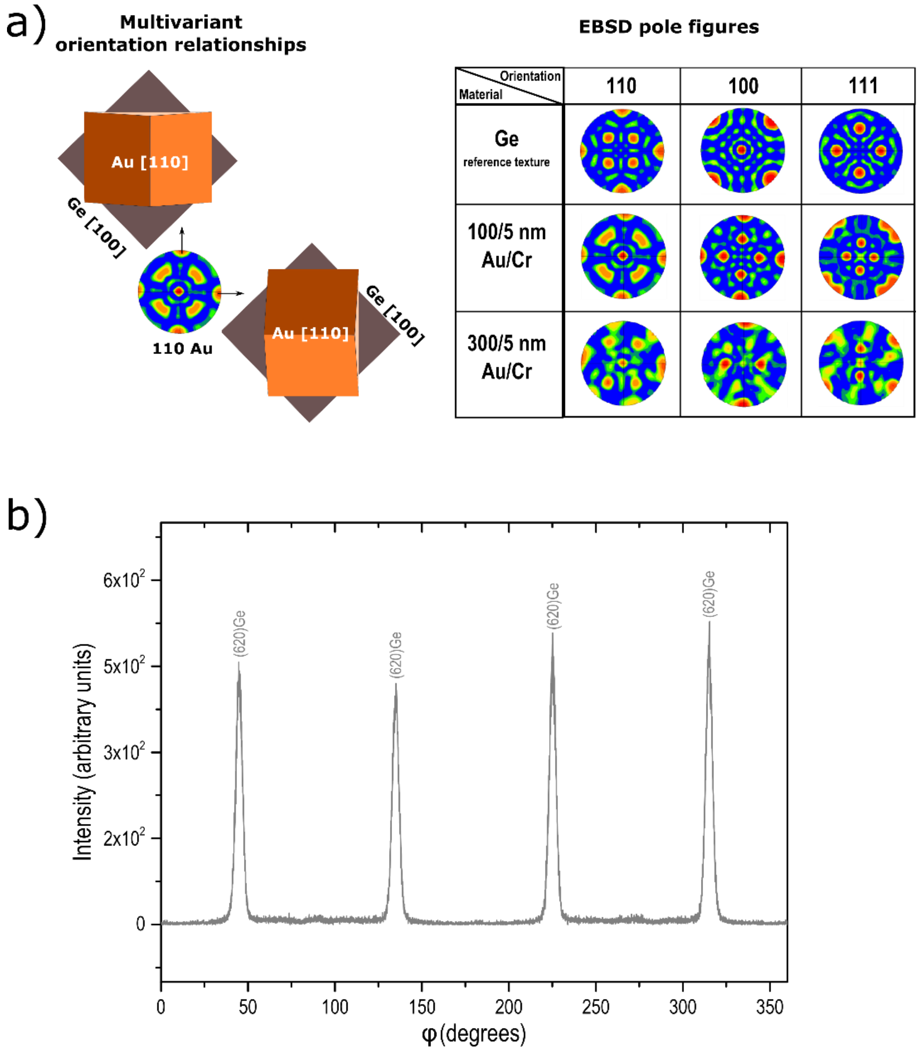

Figure S3: **Orientation relationships between Au and Ge. a.** EBSD analysis on 100, 300 nm Au (5 nm Cr) shows multi-variant [110]Au on [100]Ge. **b.** Reference φ scan of the (620)Ge substrate plane.

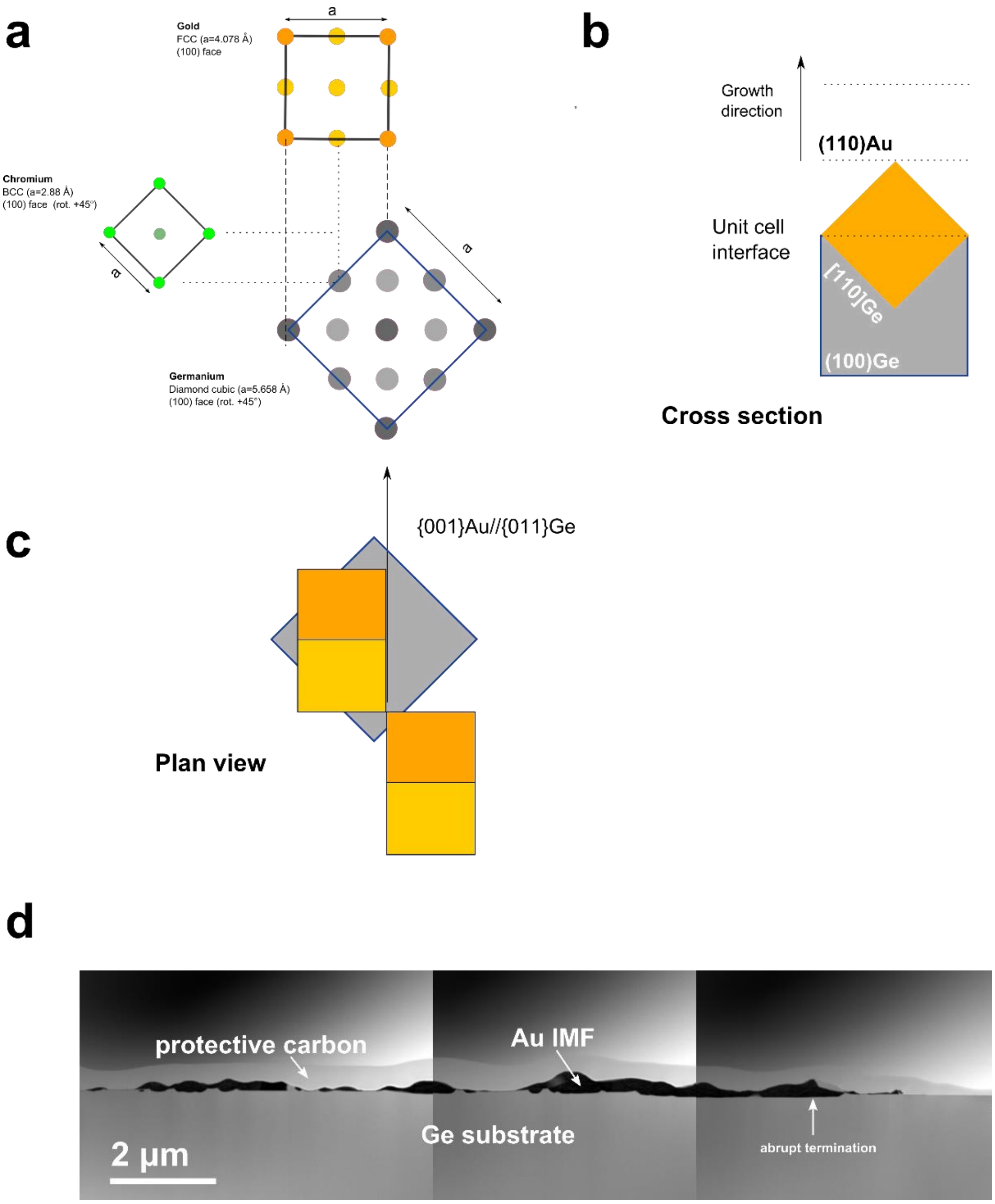

Figure S4: **Schematic diagrams explaining choice of Au/ Cr on Ge. a.** Lattice diagrams of Au, Ge and Cr unit cells show their compatibility as a super structure. **b.** Preferred (110) Au growth on Ge. **c.** Orientation relationship between Au and Ge shown in plan-view. **d**. Bright field TEM showing abrupt interfaces of the IMF to Ge. Cracked Cr regions result in some outward Ge exchange. The interface appears displaced in these regions, relative to the horizon.

Material selection and nature of interfaces.

Au forms a low temperature eutectic with Ge and has a naturally occurring heteroepitaxy with Ge. In order to maximize hot carrier lifetime, it is necessary to seek a metallization sequence that would result in non-close packed crystallization. Au/Cr and Ge lattices are compatible in this regard, as illustrated in the schematic shown in Fig. S4.a. This material combination assists epitaxial stabilization and non-close packed crystallization in the metal. Other metals may produce similar results but their size and gap specifications may vary according to their preferred crystal orientation. Most FCC metals prefer the (111) close packed form. Au/ Ge forms a special case due to heteroepitaxy from liquid interfaces. Preferred crystallization and orientation relationships to the substrates observed in Fig. 3.c, Fig. S3 are illustrated schematically in Fig. S4.b. and Fig. S4.c. respectively. The IMF forms abrupt interfaces to Ge, confirmed in bright field TEM shown in Fig. S4.d.

Here, the islands are formed by rapid annealing and a significant eutectic mixing occurs during the process, following which the film crystallizes due to fast cooling, forming IMFs. The interfaces formed to the substrate are mediated by inward and outward liquid transport of material as opposed to diffusion.

Spiking will not be an issue if the annealing process is controlled. XRD results in Fig. 3.c and Fig. 3.d, combined with EBSD pole figures in Fig. S3.a. confirm uniform crystallinity and texture in thin IMFs formed over a large area. Even very small Au islands crystallize in the (110) orientation on Ge, as shown in ref. 16 (2017, Jany *et al*). The annealing temperature and cooling rate plays a crucial role in the final crystal formations that occur in the material. Fast cooling assists (110) recrystallization in Au, which enhances hot carrier lifetime as shown in ref. 18 (2015, Bernardi).

Similar ohmic contacts were obtained for n- and p- Si using Au/Cr IMFs but these data are not reported in this work. Furthermore, the role of Au as an amphoteric dopant has previously been identified in Si. The Fermi level pinning problem is not as severe in Si as it is in Ge and this is why the main focus of this work has been on Ge. The mechanism of electron-electron heating will apply to all nanoscale metals.