Non-invasive imaging of three-dimensional integrated circuit activity using quantum defects in diamond

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The continuous scaling of semiconductor-based technologies to micron and sub-micron regimes has resulted in higher device density and lower power dissipation. Many physical phenomena such as self-heating or current leakage become significant at such scales, and mapping current densities to reveal these features is decisive for the development of modern electronics. However, advanced non-invasive technologies either offer low sensitivity or poor spatial resolution and are limited to two-dimensional spatial mapping. Here we use shallow nitrogen-vacancy centres in diamond to probe Oersted fields created by current flowing within a multi-layered integrated circuit in pre-development. We show the reconstruction of the three-dimensional components of the current density with a magnitude down to $\approx 10 \mu A/\mu m^2$ and sub-micron spatial resolution capabilities at room temperature. We also report the localisation of currents in different layers and observe anomalous current flow in an electronic chip. Further improvements using decoupling sequences and material optimisation will lead to nA-current detection at sub-micron spatial resolution. Our method provides therefore a decisive breakthrough towards three-dimensional current mapping in technologically relevant nanoscale electronics chips.

INTRODUCTION

The rapid growth and downscaling of silicon integrated circuits (ICs) have ushered revolutions in many areas of today’s society [1–4], such as high-speed internet [5], in-car navigation [6] and leadless pacemakers [7]. However, if the semiconductor community has underpinned Moore’s law [8] for over 50 years by shrinking the size of electronic components, the scaling roadmap is nearing its end [1, 9]. Hence, next-generation technologies like autonomous driving [10] or quantum processors [11] rely on a new strategy: three-dimensional chip architectures [12–14]. In this regard, device development, optimisation and failure analysis are severely challenged due to the absence of methods for direct visualisation of three-dimensional charge flow. This concerns particularly multi-layer chips with sub-micron feature sizes. Most electric current imaging techniques visualise charge transport through the associated magnetic fields that pass unaffected through the materials used in semiconductor devices. One approach consists of delaying the chip to probe fields with a micro-needle [14]. Non-destructive current imaging can be implemented using superconducting quantum interference devices (SQUID) microscopes, but the inherent stand-off distance limits the spatial resolution to tens of micrometres [16]. Conversely, giant magneto-resistance (GMR) microscopes provide excellent spatial resolution at the expense of much lower field sensitivities [17, 18]. Importantly, SQUID and GMR microscopes are only sensitive to a single magnetic field component, limiting reliable current imaging to the two-dimensional realm.

In this article, we demonstrate non-invasive current imaging in three-dimensional integrated circuit using quantum sensors at room temperature. We use nanoscale nitrogen-vacancy (NV) centres in diamond [19, 20] which offer the unique property to probe all three vectorial components of a magnetic field simultaneously [21, 22]. Besides, NV centres operate under a wide span of external conditions [23–27], demonstrate excellent sensitivity to magnetic fields [28, 29] and enable nanoscale spatial resolution [30]. Pioneering work successfully demonstrated IC activity imaging [31, 32] but has been so far restricted to a two-dimensional study. In this work, we leap a step forward by demonstrating imaging of three-dimensional current distribution within a micro-chip used as an mm-wave test circuit for automotive radar applications. For this, we employ an NV-based wide-field microscope described in Figure 1c, which allows us to synchronously map vectorial magnetic fields over a region of $90 \mu m \times 90 \mu m$ (see Methods). We use the instrument to measure the current density flow in the multi-layered IC (Figure 1b), notably without using prior knowledge about its design.

CURRENT DENSITY IMAGING USING NV CENTRES

The principle of the experiment is depicted in Figure 1c. Long-range magnetic fields, also known as Oersted...
fields, are created by moving charges according to the Biot-Savart law (eq. (1))
\[
\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \int \left( \mathbf{J}(\mathbf{r}') \times \frac{(\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} \right) d^3r
\]
where \(\mu_0\) is the vacuum permeability, \(\mathbf{r}\) is the spatial coordinates at the observation point, and \(\mathbf{J}(\mathbf{r}')\) is the current distribution in the source plane.

Magnetic field isolines in Figure 1c show that magnetic field contributions merge with distance from the current source, resulting in blurry patterns. In our experiment, we place a diamond homogeneously implanted with near-surface NV centres in the vicinity of the IC. The electron spin of each NV centre is affected by the magnetic field via the Zeeman interaction \(\mathcal{H}_{\text{Zeeman}} = -\gamma_{\text{NV}} \mathbf{B} \cdot \mathbf{S}\) where \(\gamma_{\text{NV}}\) is the NV-associated electron spin gyromagnetic ratio, \(\mathbf{B}\) is the total magnetic field in the vicinity of the NV centre and \(\mathbf{S}\) represents the spin operators for the electron spin with \(S = 1\). Probing this Zeeman interaction on the multiple NV orientations, naturally occurring in the diamond lattice (Figure 1d), is done by performing optically detected magnetic resonance (ODMR) on the NV centres.

We perform the experiment on two chips: an operational device and a defective one. Investigation of both samples under light-microscopy (Figure 2a,b) reveals no difference. On the contrary, mapping the Oersted fields exposes the failure immediately. With the operating device, Figure 2c shows Oersted fields clearly reflecting the geometry of the underlying structure. In Figure 2d, we can see that the defective device produces nearly one order of magnitude lower magnetic fields (a maximum amplitude of \(|B_z| = 513(6) \mu T\) compared to \(73(5) \mu T\)). Furthermore, the magnetic field maps \(B_y\) and \(B_z\) produced by the defective chip show a different unstructured pattern. To better understand the current distribution producing such Oersted field patterns, we reconstruct the lateral current density \(J_{xy}\). We follow the procedure de-
FIG. 2. Vectorial Magnetic field produced by the current-carrying wires: operational case vs failure case and corresponding current density maps. a-b) Optical images of the operational and defective IC, respectively. c-d) Mapping of the three vectorial magnetic field components $B_x, B_y, B_z$ produced by the operational and defective IC, respectively. The sign gives the direction of the field. Line cuts at $x_C, x_C', y_C, y_C'$ are shown in Figure 3(a,b) for deeper analysis. Line cuts at $x_C, x_C', y_C, y_C'$ are shown in the Supplementary Information. e-f) Corresponding in-plane current density map reconstructed from $B_x$ and $B_y$ in (a) and (b) respectively. Red arrows represent the flux lines of the current densities. Scale bars are 10 µm wide.

scribed in references [33, 34] and use the components of the magnetic field $B_x$ and $B_y$ to numerically invert the Biot-Savart law (eq. (1)), resulting in the current density shown in Figure 2f (see Supplementary Information). The maps show the lateral current density amplitude $|J_{xy}|$ integrated over the vertical axis $z$. In the operating device (Figure 2), the current paths follow the shape of the visible structure in Figure 2a. A closer look at the central part of the map reveals a weak current contribution with wide lateral spreading, indicating that additional currents flow underneath. Moreover, the flow appears significantly weaker in some parts of the circuit, like at the sharp corners. In the defective device (Figure 2), several current sources produce fields of similar intensity and observing $|J_{xy}|$ alone is insufficient to comprehend the anomalies in the current path. To further understand these observations, we investigate the different layer contributions to locate the flow within the device and seek the third dimension of the current density, $J_z$.

LOCALISATION OF CURRENTS INSIDE A MULTI-LAYERED DEVICE

To resolve the signal in the vertical direction $z$, we investigate different linecuts along $x$ in the magnetic field map $B_x$ (Figure 3a,b). We fit the linecuts with the Biot-Savart model (Equation (1)), using the infinite wire approximation (Equation (2)),

$$B_{x,y} = \frac{\mu_0 I_{y,z} \Delta z}{2\pi \sqrt{[r_{xy} - r_{wire}]^2 + \Delta z^2}} + o$$

where $I_{y,x}$ is the lateral current amplitude, $r_{xy}$ represents the observation position on the $xy$-plane, $r_{wire}$ the position of the current source on the $xy$-plane, $\Delta z$ is the distance between the current source and the observation position on the vertical axis $z$ and $o$ is a constant offset. The fitting procedure reveals a contribution from two layers: the first one at $\Delta z_1 = 4.5(5) \mu m$ away from the layer of NV centres and the second one at $\Delta z_2 = 8.5(8) \mu m$ (see Supplementary Information). In the operating (failure) case, we identify a current of amplitude $I_A$ ($I_A'$) in the main lead dividing into currents of amplitude $I_{B1}$ ($I_{B1'}$) and $I_{B3}$ ($I_{B3'}$) in two further leads (Figure 3a,b). When comparing the results from the defective device to the operating one, most loss appears on the outer layer (at $\Delta z_1$), presenting one order of magnitude lower current amplitude. In contrast, the deeper layer (at $\Delta z_2$) presents a smaller loss. Finally, the analysis of other line profiles reveals another current contribution at $\Delta z_2$ present in the operating and defective devices, in both cases with no apparent anomaly (see Supplementary Information). From these observations, we conclude that failure happens in the layer at $\Delta z_2$ and then affects the outer layer by propagation.

Overall, the simple model with infinite wire approximation already shows excellent agreement with the experimental data. In order to verify the consistency of the procedure, we now perform a simulation of Oersted fields
produced by a multi-layered chip. The simulation reproduces the layering of the chip, made of a SiGe technology described in [35], and some of the apparent geometric features for guidance only.

The total thickness of the simulated structure is 11.8 µm and combines twelve stacked layers (Figure 1). As depicted in Figure 3a, two layers across the structure are electrically active and labelled as 1st, 2nd active layer (AL) and through-silicon vias (TSV) connect the 1st AL to the bottom layer of the structure. We investigate magnetic fields generated by this structure, resulting in patterns at the position of the sensors shown in Figure 4b. Similarly to the experimental observations (Figure 2), the contribution from the 1st AL is clearly defined and unambiguously related to the shape of the structure. The contribution from the 2nd AL shows a pronounced lateral spreading, and the signal arising from two distinct wires starts to blur out. Finally, the contribution from the vertical current is weak due to both the observation position and the presence of counter-propagating flows which average out magnetic field contributions (see Supplementary Information). Still, a current propagating vertically has a nonzero contribution in $B_{xy}$ in contrast to its contribution in $B_z$. Therefore, currents propagating in the $z$ direction can be sensed by NV centres contrary to systems such as SQUIDs (see Supplementary Information).

Lastly, to precisely study the flow in the three-dimensional structure and observe vertical currents, we infer information about the third component of the current density, $J_z$.

**THREE DIMENSIONAL CURRENT DENSITY MAPPING**

The current-carrying wires have a non-negligible thickness of a few hundred nanometres, leading to a possible contribution of the current’s $z$–component. In order to precisely evaluate the total current density, we now consider a component $J_z \neq 0$ in eq. (1) (see Supplementary Information). The resulting maps are shown in Figure 5a-c, and as for the current density images in Figure 2, they show an integrated signal over the vertical axis $z$. Using the fitting algorithm employed in Figure 3 over the entire map allows us to post-select the signal from the outer layer only. Finally, by applying the current reconstruction procedure on the resulting magnetic maps, we map the three-dimensional current density flow in the outer leads (Figure 5d).

We can see in Figure 5d, a non-negligible current flow in the $z$-direction at the edges and the corners of the leads, which covers the gaps observed in Figure 2. This information is crucial for evaluating current crowding at corners in interconnect structures, which plays an essential role in nucleating voids and hence failure of ICs [36–38]. Substantially, having access to the full-vector information of the current density helps quantify and understand current flow through different stacks in layered materials. For instance, in the outer layer, we can observe a prominent $J_z$ contribution at the edge of the main branch. As for the simulation (Figure 4), this contribution is the result of counter-propagating currents. Current in the main lead flows down to a deeper layer where it splits into two paths and goes back to the outer layer. As the component $B_z$ does not carry information about $J_z$ and $B_{xy}$ shows a specific pattern with the presence of counter-propagating fields (see Supplementary Information), one can develop an algorithm using $(B_{xy} - B_z)$ with pattern recognition techniques [39] to identify the contribution from each current sources.

Resolving currents from different sources across the structure also depends on the spatial resolution of the imaging technique. NV centres offer the closest sensor-
FIG. 4. Simulation of Oersted field contributions originating from different layers. a) Geometry of the simulated structure. A layer of NV centres is separated from the chip by 0.8 µm. The structure is composed of twelve layers comprising the two AL and TSV. A current of amplitude $I_\alpha = 11.8$ mA goes to the main branch of the 1st AL, flows down to the bottom layer of the structure where it splits into two sub-path with an amplitude of $I_{\alpha 2} = \frac{I_\alpha}{2}$ and flows back to the 1st AL. In the second AL, a current of amplitude $I_\beta = 2$ mA is injected into each of the two branches which combine to a single one afterwards. b) Top view of each AL of the structure. The 1st, 2nd AL and the bottom layer of the structure are located at $z_1 = 4.5$ µm, $z_2 = 7.9$ µm and $z_3 = 12.2$ µm respectively from the sensors. c) Top: Oersted field in the $xy$-plane generated by all active components at the sensors layer position. Bottom: Separate contribution from each AL where the vertical axis shows the lateral magnetic field amplitude $|B_{xy}|$.

sample proximity known so far, but the geometry and capping layers of the microelectronics itself limit the spatial resolution to a few micrometres. In order to non-destructively resolve each layer with high resolution, the solution is to interpolate the current distribution at the source plane using additional layout information. The structure’s layout information can be obtained using circuit designs when available or using ptychographic X-ray laminography techniques [40] when the sample is unknown. Thus, combining NV-based imaging to X-ray imaging [41] will allow us to infer the complete information of nanoscale three-dimensional current-carrying structures with no prior information.

CONCLUSIONS

Using NV centres in diamond, we have demonstrated prior-free imaging of three-dimensional current density in a multi-layered integrated circuit. First, we have compared the current flow in an operational chip and a defective one. Exploiting the NV centre high dynamic range, we observed one order of magnitude lower current amplitude in the defective chip. To further understand the failure, we have shown how to localise currents originating in different leads and, in particular, decorrelating the signal originating from several stacked layers. Finally, we have presented imaging of the three vectorial components of the current density. Although the out-of-plane component of the current density $J_z$ is generally neglected in current density imaging techniques, we revealed a significant out-of-plane contribution of $J_z$ close to sharp edges.

Beyond its use for the semiconductor industry to meet the ever-increasing failure analysis needs [42], charge transport in electronic systems is fundamental to many phenomena and processes in science and technology [2, 43–45]. Therefore, unravelling three-dimensional electronic signals using our method will leverage progress in many areas. For instance, it will serve neuroimaging to overcome the limits of conventional current density imaging techniques and help to reveal new features [46]. Besides, it will help understanding fundamental open problems in three-dimensional correlated systems [47, 48].

Over the past decade, many efforts have been deployed to both improve the sensing capabilities of the NV centres [49–53] and to develop techniques to explore new regimes [54–57]. These combined advances led to remarkable achievements such as revealing electric fields associated with surface band bending in diamond [58] and probing Johnson noise in metals [59]. The advancements
Experimental set-up and measurement

The NV imaging set-up is a custom-built wide-field fluorescence microscope similar to the one used in [22, 53]. The microscope consists of an air objective (Olympus MPLAPLON 50×, NA = 0.95), a 650 nm long-pass filter (Omega), a 300 nm tube lens and a Cascade II:512 CCD camera (512 × 512 pixels, Photometrics), resulting in an effective pixel width of about 192 nm on the object side.

Experimental realisation of continuous-wave ODMR data was achieved by exciting NV centres with a 532 nm laser (Coherent) gated with an acousto-optical modulator (Crystal Technology) and coupled into the optical path with a dichroic mirror (Semrock). Simultaneously, microwave radiations were generated using an MW source (Rhode&Schwarz SMBV100A) and amplified (100S1G4, Amplifier Research) before being sent to a 50 μm-thick copper wire. The resulting MW power sent to the wire was approximately 30 dBm. For all the measurements reported in the main text, the total continuous-wave laser power at the back aperture of the objective was about 90 mW. The camera settings were set to 2 × 2 pixel-binning and the field of view (FOV) was defined to be 90 μm × 90 μm.

The IC chip was wire bonded to a printed circuit board (PCB) with 20 μm-thick gold wires. The PCB was electrically connected to a power supply (Rhode&Schwarz Hameg) generating 3.3 V of supply voltage needed to run the chip and an additional 2 V bias signal was used to vary the total current sent to the main circuit. All measurements were performed in an ambient environment at room temperature, under a bias magnetic field |B0| ≈ 5.5 mT generated using a permanent magnet thermally stabilised at a temperature of ≈ 37 °C.

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