Broadband image sensor array based on graphene–CMOS integration

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Integrated circuits based on complementary metal-oxide-semiconductors (CMOS) are at the heart of the technological revolution of the past 40 years, enabling compact and low-cost microelectronic circuits and imaging systems. However, the diversification of this platform into applications other than microcircuits and visible-light cameras has been impeded by the difficulty to combine semiconductors other than silicon with CMOS. Here, we report the monolithic integration of a CMOS integrated circuit with graphene, operating as a high-mobility phototransistor. We demonstrate a high-resolution, broadband image sensor and operate it as a digital camera that is sensitive to ultraviolet, visible and infrared light (300–2,000 nm). The demonstrated graphene–CMOS integration is pivotal for incorporating 2D materials into the next-generation microelectronics, sensor arrays, low-power integrated photonics and CMOS imaging systems covering visible, infrared and terahertz frequencies.

Here, we present monolithic integration of graphene with a CMOS integrated circuit. In this case, the integration potential is shown by the realization of an image sensor with a 388 × 288 array of graphene–quantum dot photodetectors that is operated as a digital camera with high sensitivity for both visible and short-wave infrared light. The ∼110,000 photoconductive graphene channels are all individually integrated vertically, connecting to the individual electronic components of a CMOS readout integrated circuit (ROIC). The chip containing the circuitry is similar to those used for commercial image sensors in digital cameras, commonly used in smartphones, but here operating for both visible and short-wave infrared light (300–2,000 nm). So far, it has not been possible to operate monolithic CMOS image sensors for this wavelength range. Therefore, a broadband sensing platform that is monolithically integrable with CMOS is highly desirable. This proof-of-principle monolithic CMOS image sensor is a milestone for low-cost and high-resolution broadband and hyperspectral imaging systems15, with applications in safety and security, smartphone cameras, night vision, automotive sensor systems, food and pharmaceutical inspection, and environmental monitoring16.

Device structure and functionality

The integration of our CMOS graphene–quantum dot image sensor is a back-end-of-line process schematically shown in Fig. 1a. The process starts with the transfer of graphene onto a CMOS die that contains the read-out circuitry of the image sensor. Now, each pixel structure is covered with a layer of graphene that is connected with the bottom readout circuitry through vertical metal interconnects (Fig. 1b,c). Next, graphene is patterned to define the pixel shape as shown in Fig. 1d (inset 2 and Supplementary Fig. 1). Finally, a sensitizing layer of lead sulfide (PbS) colloidal quantum dots (CQDs) is deposited via a simple spin-casting process, on top of the graphene layer.

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The photoresponse is based on a photogating effect as follows: light is absorbed in the CQD layer followed by transfer of photogenerated holes (or electrons) to the graphene, where these circulate due to a bias voltage applied between the two pixel contacts (illustrated in Fig. 1b). Therefore, the photosignal is sensed as a change in the conductance of the graphene transport layer. Owing to a high mobility of graphene (here \( \mu > 1,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)), this photoconductor structure exhibits ultrahigh gain of \( 10^8 \) and responsivity above \( 10^7 \text{ AW}^{-1} \), which is a strong improvement compared with photodetectors and imaging systems based on quantum dots only. The 1/f noise, the dominating noise source in graphene–quantum dot detectors (Supplementary Notes and Supplementary Fig. 8), can be described by the empirical Hooge relation: 

\[
\frac{S_f}{I_f^2} = \alpha_H (N_f)
\]

where \( S_f \) is the current noise power spectral density, \( I_f \) is the current, \( \alpha_H \) is the Hooge parameter, \( N_f \) is the total number of carriers in the system and \( f \) is the frequency. \( S_f/I_f^2 \) is low in the graphene–quantum dot detector as graphene is a semimetal and has a Hooge parameter that is more than an order of magnitude smaller than high-quality silicon. The large signal and low noise lead to a measured detectivity above \( 10^{12} \text{ cm} \text{ Hz}^{1/2} \text{ W}^{-1} \) (Jones) for our individual photodetector prototypes. This large detectivity, spectral sensitivity from 300–2,000 nm, and recently demonstrated switching times of 0.1–1 ms clearly validate the applicability for infrared imaging. Apart from the array of photosensitive pixels, the imager contains a row of blind pixels that are used to subtract the dark signal as the photodetectors are voltage biased. We remark that here, the spectral range is determined by the quantum dot material and size, but this approach can be generalized to other types of sensitizing material to extend or tune the spectral range of the sensor element.

The functional elements of the CMOS circuitry are shown in Fig. 1b–d. The elements surrounding the active pixel area provide multiple functions: signal path control, photodetector biasing, tunable compensation resistors, blind pixels, amplification and feedback circuitry. The CMOS circuitry is designed to optimize low-noise and low-power operation. The circuit includes bias circuitry and tunable compensation resistors, blind pixels, amplifiers and feedback paths.
read-out of the photosignal from pixel to output, and control of the
image exposure and shutter operation. The photosignal per pixel is
acquired through a balanced read-out scheme, as shown in the sche-
matic in Fig. 1b, that consists of the blind pixel (with resistance \( R^{\text{blind}} \)) and a tunable compensation resistance \( R^{\text{comp}} \) in series with the pixel
resistance \( R^{\text{pixel}} \) that can be digitally controlled for each individual
dividend. Pixels are addressed sequentially on a row-by-row basis (rolling shutter) with a frame rate of maximally 50 frames per
second (f.p.s.), limited by the design of the ROIC. At this frame
rate the power consumption of the ROIC is 211 mW. The signal
readout chain (Fig. 1b and Supplementary Fig. 5) is based on a capa-
citive transimpedance amplifier (CTIA) per column that integrates
the current difference between photosensitive and blind pixels. The
amplifier output is sampled, before and after exposure, in a storage
block, also per column, and all column signals are multiplexed into
a common output bus terminal. Finally, a correlated double sampling
(CDS) correction is performed to reduce readout noise and the
resulting output signal \( V^{\text{out}} \) is sent to the imager’s analog output.

Digital camera

We first present the main results of our work in Fig. 2, which shows
several types of image that have been captured with our prototype
digital camera comprising the graphene–CMOS image sensor. The
configuration for obtaining these images is schematically illustrated
in Fig. 2a: the graphene–quantum dot image sensor captures reflection
images from objects illuminated by a light source. The greyscale
plots of Fig. 2 are compiled of the normalized photo-signals for each of
the photodetection pixels of the \( 388 \times 288 \) array, amplified and
multiplexed by the CMOS integrated circuit. Not all of the active
area of the image sensor is covered with graphene due to the finite
size of the CVD graphene sheet and manual alignment of the
transfer (Supplementary Notes and Supplementary Fig. 7); the
pixels that were not covered with graphene and hence did not show
any conductance are represented as continuous grey areas. The
image shown in Fig. 2c was obtained using an image sensor
with CQDs that have an exciton peak at \( \sim 1,000 \) nm; Fig. 4a) photograph of a standard image
reference ‘Lena’ printed in black and white on paper illuminated with an LED desk lamp. d, VIS, NIR and SWIR photograph of a box of apples, illuminated
with the same source as in b, but without the 1,100 nm long-pass filter. e, f, NIR and SWIR image of a rectangular block covered in fog (e) as shown in f,
showing that fog is transparent for SWIR light. g, h, NIR and SWIR image of a rectangular block behind a silicon wafer (g) as shown in h, showing that silicon
is transparent for SWIR light. i, j, NIR and SWIR image of a glass of water (i) as shown in j, showing that water absorbs SWIR light. For e, g, i, the same optical
setup as in b was used. A smartphone camera captured images f, h, j under office lighting conditions.

Figure 2 | Hybrid graphene–CQD-based image sensor and digital camera system. a, Digital camera set-up: the image sensor plus lens module captures the
light reflected off objects that are illuminated by an external light source. Supplementary Fig. 3 contains all the details of the image-capturing set-up for each
of the images shown. b, Near-infrared (NIR) and short-wave infrared (SWIR) light photograph of an apple and pear. An incandescent light source (1,000 W,
3,200 K) illuminated the objects. As this image sensor is sensitive to visible (VIS), NIR and SWIR light (300–1,850 nm; Fig. 4b), we placed a 1,100 nm long-
pass filter in the optical path to reject all light that a conventional Si-CMOS sensor can capture. The tickmarks indicate the column (horizontal axis) and row
(vertical axis) numbers. The illumination yielded an irradiance on the image sensor of \( \sim 1 \times 10^{-2} \) W cm\(^{-2}\). The greyscale represents the photosignal \( dV \) in volts
(dV = \( V^{\text{out,light}} - V^{\text{out,dark}} \)) normalized to \( dV \) obtained from a white reference image. An image-processing scheme, as described in
the Supplementary Methods, was performed. c, VIS and NIR (this image sensor is sensitive to 300–1,000 nm; Fig. 4a) photograph of a standard image
reference ‘Lena’ printed in black and white on paper illuminated with an LED desk lamp. d, VIS, NIR and SWIR photograph of a box of apples, illuminated
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is transparent for SWIR light. i, j, NIR and SWIR image of a glass of water (i) as shown in j, showing that water absorbs SWIR light. For e, g, i, the same optical
set-up as in b was used. A smartphone camera captured images f, h, j under office lighting conditions.
subtract the dark signal. To this end, we have chosen an S-shaped function of the photosensitive pixels with the blind pixels, to properly match the yield of the graphene transfer, channel patterning and contact resistance values in a 10 × 10 pixel area are all close to 20 kΩ.

The variation in the pixel resistance (R_pixel) is most likely due to strain effects and unintentional doping. The issue of variable graphene device resistance is ameliorated by utilizing the tunable series resistor (R_comp) in the CMOS circuit, which can be digitally addressed and optimized for each individual pixel (Supplementary Notes and Supplementary Fig. 6). The results of this tunable matching are visible in the resistance histograms shown in Fig. 3b. This histogram reveals that after optimization with the compensation resistor R_comp for each pixel, a rather narrow distribution of pixel resistances is obtained with a spread of ~4 kΩ around an average value of 20 kΩ. This moves the resistance of most of the pixels inside the operation regime of the ROIC. Moreover, a great improvement in the detector yield, performance and uniformity across all the pixels is achieved.

This can be inferred from detector performance measurements, which monitor the dependence of the detector signal on the irradiance for each pixel. In combination with measurements of the detector noise (Supplementary Fig. 8), the key figure of merit for the detector sensitivity can be extracted: the noise-equivalent irradiance (NEI). An example for one specific pixel is shown in Fig. 3d, from which we infer a photosensitivity down to a NEI level of 10^-10 W cm^-2, which corresponds to the irradiance from a quarter moon.

A complete map of the sensitivities (expressed in terms of the NEI) of all the pixels of the imager is shown in Fig. 3c, revealing that more than 95% of the pixels are sensitive to irradiance corresponding to partial-moon and twilight conditions in the visible range. Infrared images demonstrates imaging applications that are impossible with the widely used silicon CMOS cameras.

Monolithic graphene–CMOS integration performance

Key to graphene integration with the CMOS electronic circuit is a reliable and high-quality electrical connection between all (~111,744) the graphene conduction channels and the integrated circuitry through vertical metal plugs. A 2D map of the conducting and non-conducting pixels, obtained through the read-out circuitry of the ROIC, is shown in Fig. 3a. Within the area where graphene is present, a resistance was recorded for 99.8% of the pixels, and hence the yield of the graphene transfer, channel patterning and contacting is close to unity. In addition, it is important to match the resistance of the photosensitive pixels with the blind pixels, to properly subtract the dark signal. To this end, we have chosen an S-shaped graphene channel targeting a resistance of 20 kΩ to make it compatible with this specific ROIC that has an operation regime from 20–100 kΩ. (We remark that the S-shaped graphene channel limits the fill factor of the photoactive area. This limitation can be solved by proper ROIC design optimized for graphene–quantum dot photodetectors, in principle allowing for fill factors close to 100%; Supplementary Notes and Supplementary Fig. 9.) Using that same read-out circuitry we could also obtain the resistance values for each of the conducting pixels. The inset of Fig. 3a shows that the resistance values in a 10 × 10 pixel area are all close to 20 kΩ.

Figure 3 | Electro-optical characterization. a, Map of the conducting (blue) and non-conducting (grey) pixels. The dashed box indicates the area over which the yield was calculated. Inset: 3D bar plot of the total resistance per pixel (R_pixel + R_comp) values for a 10 × 10 pixel area (green square). Green, R_pixel; blue, R_comp. b, Histogram of R_pixel before resistance compensation and after compensation (R_pixel + R_comp). R_comp varies from 0 to 8 kΩ. c, Histogram of the NEI for all pixels inside the dashed box in a, plotted per column (in total 255 pixels for each column). Light blue, pixels that are sensitive to moonlight; dark blue, pixels that are sensitive to twilight; black, pixels that are not sensitive to light. d, Photosresponse versus power at uniform illumination with λ = 633 nm and measured from twilight (~10^-4 W cm^-2) down to starlight (10^-10–10^-7 W cm^-2) conditions. The green crosses are data obtained from a representative pixel in the image sensor. Blue and purple circles represent photoresponse (expressed in light-induced resistance change dR/R) of a reference photodetector with the same type of CQDs and a channel of 48 µm width and 8 µm length. The data points in blue are obtained using a d.c.-coupled amplifier with a bandwidth of 100 Hz. The data in purple are obtained using a lock-in-type measurement technique at 100 Hz modulation. The images below the plot illustrate the illumination conditions: from starlight to moonlight to twilight.
range (for a wavelength of 633 nm). The dynamic range of the imager is limited by the readout circuit because the graphene–CQD pixel conductance does not match the optimum conductance for which this off-the-shelf ROIC has been designed. For comparison, we show the complete electro-optical characterization of the image sensor as well as individual reference photodetectors in Figs 3d and 4d, and Supplementary Table 1. We find that low-frequency 1/f noise dominates the detector noise (Supplementary Fig. 8), but owing to the high responsivity, high sensitivities (and thus low NEI) have been obtained. Reference photodetectors can operate stably at much smaller NEI (down to $10^{-9}$ W cm$^{-2}$), have a dynamic range above 80 dB and a speed 1000 f.p.s. (Fig. 4d inset). Customizing the readout circuitry would allow reaching the sensitivity and dynamic range of an individual reference photodetector in an imaging system. Therefore, customized readout chips for graphene–CQD pixels would enable operation at higher frame rates and detection sensitivities that are comparable to commercial imaging systems, with the advantage that our system is sensitive to UV, visible, near-infrared and short-wave infrared light and can be monolithically integrated with CMOS.

**Broadband imaging system**

We further demonstrate this extensive spectral range in Fig. 4a,b, showing the photoresponse spectra for two different imagers based on two different sizes of CQDs that are deposited on top of the graphene layer. The spectra of these imagers are based on PbS CQDs with exciton peaks at 920 nm and 1,670 nm, but the position of the exciton peak in this material system can be readily tuned from <700 nm to >2,200 nm by tuning the size of the quantum dots. Further extension into the mid-infrared can be achieved by switching to alternative low-bandgap CQDs$^{39}$. The synthesis of dots can be implemented in a low-cost continuous-flow process. The detection sensitivity reaches from ultraviolet up to 1,850 nm for the imager with CQDs with an exciton peak of 1,670 nm. To demonstrate the capability for night-vision applications, Fig. 4c shows the detection by an individual detector of the ‘night glow’, which is the emission of short-wave infrared light by the Earth’s atmosphere that can be utilized for passive night vision$^{41}$. By aiming our detector at a dark and clear sky, the night-glow signal in Fig. 4c is clearly distinguished from the noise (Supplementary Methods and Supplementary Fig. 4).

**Conclusions and outlook**

Future graphene-based image sensors can be designed to operate at higher resolution, in a broader wavelength range, and potentially even with a form factor that fits inside a smartphone or smartwatch (Supplementary Notes and Supplementary Fig. 9). In contrast to current hybrid imaging technologies (which are not monolithic), we do not encounter fundamental limits with respect to shrinking the pixel size and increasing the imager resolution. Graphene patterns and contacting, that is, lithography, will ultimately be the limiting factor. Therefore, competitively performing image sensors with multi-megapixel resolutions and pixel pitches down to 1 µm are within reach (Supplementary Table 2).

The confirmation that a complex graphene–CMOS circuit is operational paves the way for a wide range of electronic and optoelectronic technologies where monolithic integration is essential, such as integrated photonics, high-frequency electronics, and arrays of sensors. Future development of the transfer and encapsulation of graphene (for example, based on hexagonal boron nitride$^{39}$) will further increase the uniformity and performance of graphene–CMOS technologies. A further compelling future prospect is the creation of 3D integrated circuits based on 2D materials with Si-CMOS that can perform even more complex tasks. For example, the layer-by-layer stackability of graphene and other 2D materials opens a wealth of possibilities to add electronic and

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**Figure 4** | Visible, near-infrared and short-wave infrared sensitivity, and night glow measurement. a. Spectral dependence of the photoresponse for one of the pixels of the ROIC sensitized with quantum dots that have an exciton peak at 920 nm measured at a constant irradiance of $5 \times 10^{-7}$ W cm$^{-2}$. The solid blue line is a guide to the eye. Inset: absorbance spectrum of the quantum dots in solution. b. Spectral dependence of the photoresponse for one of the pixels of a ROIC sensitized with quantum dots that have an exciton peak at 1,670 nm measured at a constant irradiance of $10^{-4}$ W cm$^{-2}$. Inset: absorbance spectrum of the quantum dots in solution. c. Measurement of the night glow in terms of normalized power spectral density $N/S^2$ using a SWIR-sensitive (exciton peak at 1,670 nm) reference photodetector of $1 \times 1$ mm$^2$, aiming at a dark, clear sky for long-pass filtering with a cut-off at 1,100 nm and 1,400 nm (Supplementary Methods). The dashed lines indicate the noise level obtained with a lock-in measurement modulated at 10 Hz. The arrows denote the filter wavelength range used for collecting the data (blue bars). d. Photoresponse versus power for a reference photodetector illuminated with 1,550 nm light (blue crosses) and for the ROIC pixels in the SWIR regime, illuminated with 1,670 nm light (black crosses). The data points in blue are obtained using a d.c.-coupled amplifier with a bandwidth of 35 Hz. The reference photodetector exhibits an exciton peak at 1,580 nm and has a channel of $1 \times 1$ mm$^2$. Inset: photocurrent versus time of the reference photodetector illuminated with 1,550 nm light at an irradiance of $3 \times 10^{-6}$ W cm$^{-2}$, sampled at 10 kS s$^{-1}$.
optoelectronic functions in the vertical dimension; all integrated into CMOS microelectronic and optoelectronic circuits.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions
S.Go planned and supervised the experiments and wrote the manuscript. G.N. designed and fabricated the devices and performed measurements. C.M. performed measurements and data analysis. S.Ga synthesized materials and contributed to material characterization. J.P. developed measurement procedures, and contributed to planning of the experiment. R.P. and G.B. developed fabrication procedures. T.G. and I.N. contributed to device fabrication and characterization. J.J.P. developed measurement procedures, and contributed to planning of the experiment. R.P. and G.B. developed fabrication procedures. T.G. and I.N. contributed to device fabrication and characterization. E.P. contributed to measurements. T.L. contributed to device fabrication and characterization. R.P. and G.B. developed fabrication procedures. T.G. and I.N. contributed to device fabrication and characterization. E.P. contributed to measurements. T.L. contributed to the synthesis of materials. A.C., A.P. and A.Z. provided materials. F.K. and A.P. provided materials. F.K. and A.P. contributed to measurements. T.L. contributed to device fabrication and characterization. E.P. contributed to measurements. T.L. contributed to the synthesis of materials. A.C., A.P. and A.Z. provided materials. F.K. and A.P. supervised the study and wrote the manuscript. All authors provided input to data analysis, discussed the results and assisted in manuscript preparation.

Additional information
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