Switchable metasurfaces can actively control the functionality of integrated metadevices with high efficiency and on ultra-small length scales. Such metadevices include active lenses, dynamic diffractive optical elements, or switchable holograms. Especially, for applications in emerging technologies such as AR (augmented reality) and VR (virtual reality) devices, sophisticated metaoptics with unique functionalities are crucially important. In particular, metaoptics which can be switched electrically on or off will allow to change the routing, focusing, or functionality in general of miniaturized optical components on demand. Here, we demonstrate metalenses-on-demand made from metallic polymer plasmonic nanoantennas which are electrically switchable at CMOS (complementary metal-oxide-semiconductor) compatible voltages of ±1 V. The nanoantennas exhibit plasmonic resonances which can be reversibly switched ON and OFF via the applied voltage, utilizing the optical metal-to-insulator transition of the metallic polymer. Ultimately, we realize an electro-active non-volatile multi-functional metaobjective composed of two metalenses, whose unique optical states can be set on demand. Overall, our work opens up the possibility for a new level of electro-optical elements for ultra-compact photonic integration.
using nanoantennas from smart functional materials with electrically driven metal-to-insulator transitions would allow to turn a metalens and thus its functionality fully ON or OFF on demand. Here, we demonstrate, for the first time, active metalenses-on-demand and a multi-functional metaobjective composed of electrically switchable metallic polymer nanoantennas. The plasmonic metalenses are switchable between fully ON- and OFF-states via an applied voltage of only ±1 V. A detailed comparison of our approach for such electroactive metasurfaces/lenses to existing work discussed above is shown in Table S1 in the Supplementary Information.

**Results and discussion**

The concept of our metallic polymer metalenses and metaobjective is illustrated in Fig. 1. The objective consists of two independent electrically switchable metalenses (polymer metalens 1 and 2), placed on an ITO (indium-tin-oxide) coated substrate and separated by an electrolyte (Fig. 1a). Each metalens comprises plasmonic polymer nanoantennas which are switchable between a metallic and insulating state via applied voltages of +1 V and −1 V, respectively. This is illustrated in the lower part of Fig. 1a. In particular, the plasmonic resonance of the nanoantennas can be switched fully ON or OFF electrically. The underlying mechanism is an electrochemically driven optical metal-to-insulator transition in the metallic polymer PEDOT:PSS (poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)) (see Fig. S1 in the Supplementary Information for the dielectric functions of PEDOT:PSS in the metallic and insulating state)\(^1\). This concept is rather different from other direct approaches using nanoantennas from phase-change materials such as, e.g., GST (Germanium-Antimony-Telluride)\(^2\). These materials are typically switched by temperature, while the transitions employ a structural reorientation (e.g., amorphous to crystalline state) and thus a shift of the refractive index instead of a metal-to-insulator transition. These temperature-assisted switching mechanisms can be speed-up significantly by using resistive heating, however, this requires comparably high voltages (5–25 V)\(^3\). Consequently, in our concept a CMOS (complementary metal-oxide-semiconductor) compatible voltage of +1 V turns the nanoantenna building blocks into the metallic state and thus the individual metalens into the ON state—the refractive power of the lens is switched ON. A voltage of −1 V turns the metalens and thus the refractive power OFF. As mentioned above, a detailed comparison of our concept to other approaches is summarized in Table S1 in the Supplementary Information.

In the combined case of the metaobjective, we obtain four different output states, depending on the voltage applied to the individual polymer metalenses. These multiple states are depicted in Fig. 1b–e. In Fig. 1b, metalens 1 is turned ON (+1 V) while metalens 2 is turned OFF (−1 V). Only metalens 1 focuses the incoming collimated light beam. The metaobjective possesses a focal length \(f_1\). The inverted case in Fig. 1c (metalens 1: OFF, metalens 2: ON) causes only metalens 2 to focus the incoming light. The metaobjective possesses a focal length \(f_2\). In the third case (metalens 1: ON, metalens 2: ON), we obtain a unique multi-focal state. Due to the general working principle of our metasurfaces using a geometrical phase and circularly polarized light, the two metalenses do not influence each other. Incoming right-circularly polarized (RCP) light is focused as left-circularly polarized (LCP) light and vice-versa. This means that the focused light is cross-polarized with respect to the incident light. Both metalenses focus the incoming circularly polarized light separately and we obtain two foci, as depicted in Fig. 1d. In addition, the metallic polymer metaobjective can also be switched fully OFF. This last case with no focused light in Fig. 1e results from both metalenses to be switched OFF with an applied voltage of −1 V.

Before investigating the metaobjective, we characterize the static as well as dynamic optical properties of the individual metalens. The fabrication route is sketched in Fig. 2a: As substrate we use ITO (20 nm) covered glass to operate the final metadevices in transmission and allow electrical addressability. 90 nm of commercially available metallic polymer (PEDOT:PSS, Heraeus PH1000, Ossila) is spin-coated onto the final metadevices to deposit a 30 nm silicon-dioxide (SiO\(_2\)) layer. After lift-off, SiO\(_2\) serves as hard-mask for the subsequent argon (Ar) etching process, which removes uncovered PEDOT:PSS. As a result, we obtain a metallic polymer metalens from PEDOT:PSS.

The functionality and focal length of our metalenses depends on the curvature of the 2D quadratic phase profile, which relies on a geometric phase obtained via the geometrical arrangement and
individual rotation of the nanoantennas. The rotation angle $\varphi$ of a nanoantenna at position $x$ and $y$ is defined as

$$\varphi(x,y) = \frac{\pi}{\lambda_0} \left( \sqrt{x^2 + y^2 + f^2} - |f| \right)$$  

(1)

where $\lambda_0$ denotes the free space wavelength and $f$ the focal length. The rotation angle in dependence of the position $x$ and $y$ for a metalens with $f = 5$ mm, diameter of 1.5 mm, numerical aperture of 0.15, and illumination wavelength $\lambda = 2.65 \, \mu m$. The rotation angle in dependence of the position $x$ and $y$ for a metalens with $f = 5$ mm, diameter of 1.5 mm, numerical aperture of 0.15, and illumination wavelength $\lambda = 2.65 \, \mu m$ is depicted in Fig. 2b. It shows a typical quadratic phase profile where the incremental rotation angle decreases towards the center of the metalens. A scanning electron microscopy (SEM) image of a sub-area of the metallic polymer metalens showing the rotation angle profile of a metalens with focal length $f = 5$ mm, diameter of 1.5 mm, numerical aperture of 0.15, and illumination wavelength $\lambda = 2.65 \, \mu m$. C SEM image of a sub-area of the metallic polymer metalens showing the rotated nanoantennas. D TM plasmonic resonance of used metallic polymer nanoantennas (length 380 nm, width 160 nm, height 90 nm). Working laser wavelength ($\lambda = 2.65 \, \mu m$) marked with dashed line. E Camera images at different $z$-positions (along the optical axis) around the focal plane of the metallic polymer metalens. F Cross-section of beam profile in the focal plane of the metalens along $x$-direction. The FWHM is 81 $\mu m$. 

Fig. 2 | Fabrication and static characterization of a metallic polymer metalens. A Fabrication route to obtain the metallic polymer metalens comprising plasmonic nanoantennas. Details are given in the main text. B 2D map of nanoantenna rotation angle to obtain a quadratic phase profile of a metalens with focal length $f = 5$ mm, diameter of 1.5 mm, numerical aperture of 0.15, and illumination wavelength $\lambda = 2.65 \, \mu m$. C SEM image of a sub-area of the metallic polymer metalens showing the rotated nanoantennas. D TM plasmonic resonance of used metallic polymer nanoantennas (length 380 nm, width 160 nm, height 90 nm). Working laser wavelength ($\lambda = 2.65 \, \mu m$) marked with dashed line. E Camera images at different $z$-positions (along the optical axis) around the focal plane of the metallic polymer metalens. F Cross-section of beam profile in the focal plane of the metalens along $x$-direction. The FWHM is 81 $\mu m$. 

Please note that the theoretical diffraction-limited FWHM is on the order of 10 $\mu m$, which assumes perfect monochromatic illumination and neglects dispersion as well as aberrations. A potential reason for aberrations lies with the fabrication of our large-area polymer metalens, which is still comparably sensitive to fabrication inaccuracies. Such inaccuracies can, e.g., result from the write-field alignment of the electron-beam-lithography or from the semi-directional argon dry etching. Furthermore, the metalens with diameter 1.5 mm is designed from subunits of 100 $\mu m \times 100 \, \mu m$ write-fields. In consequence, this means that the polymer nanoantennas of the metalens will show deviations from the ideal shape/size as well as from the exact position and rotation angle. These errors can introduce aberrations such as chromatic aberration, spherical aberration, coma, and astigmatism. Furthermore, we are at the resolution limit of our IR camera (pixel size 85 $\mu m$ with 3x magnification; Effective measurement resolution in focal plane: 28.3 $\mu m$) which can cause further errors. So far, the focusing efficiency of our metallic polymer metalens is 0.8%. It is limited by
UV-sensitive glue or thermoplastic to foster integration into AR/VR. To note that the electrochemical cell can be completely air-sealed and repeatable over hundreds of switching cycles with switching frequency likely too low to be efficient. Note that the refractive index of PEDOT:PSS in the insulating/dielectric state is likely too low to be efficiently used as Mie resonator. Finally, the electro-optical switching between ON- and OFF-state is reversible and repeatable over hundreds of switching cycles with switching frequencies up to 33 Hz, as previously demonstrated.

Selected images of two cycles of electrochemical metalens switching via cyclic voltammetry (CV) are depicted in Fig. 3c (see Movie S1 in Supplementary Information for all frames including the cyclic voltammogram). CV means that the applied voltage is slowly ramped up and down between ±1 V. The images show the intensity distribution in the focal plane for different applied voltages during the switching cycles. The time axis is from left to right. The scan rate is 20 mV/s. The retractive power of the metalens is reversibly switched ON and OFF. The focused intensity is high at +1 V and low at −1 V. Interestingly, the metalens remains in the metallic ON-state for voltages down to −0.2 V. This is observable even better in the graph depicted in Fig. 3d. Here, we plot the normalized focused intensity over the applied voltage for the two full cycles. The scanning direction is indicated with arrows. In the backward scan from +1 V to −1 V, we find, that the focused intensity remains almost constant and thus the metalens remains in the ON-state down to voltages of −0.2 V. The intensity fades starting at applied voltages below −0.3 V and the metalens is switched OFF at −1 V. In contrast, in the forward scan from −1 V to +1 V the metalens remains in the OFF-state up to 0 V. From this point the focused intensity increases again until it reaches its maximum value around +1 V. The typical degradation of the optical modulation of our polymer metasurfaces is on the order of 25% after 290 switching cycles. These values are measured via chronoamperometry (CA), where the applied voltage is quickly changed between +1 V and −1 V (square-wave voltage) with frequencies of 1 Hz and 30 Hz. Figure 3d shows that the normalized focused intensity by our metalens drops by 35% after only 2 cycles of cyclic voltammetry (CV). However, as mentioned, in such CV measurements the applied voltage is slowly ramped up and down between ±1 V. Thus, one cycle of CV in Fig. 3d takes almost 4 min compared to less than a second in CA. As the degradation scales with the total time of applied voltage, the degradation in Fig. 3d is already significant after 2 long cycles of CV. Potential sources for the degradation of the polymer nanoantennas are the volume expansion of the polymer nanoantennas, the volume expansion of the liquid electrolyte, and the degradation of the polymer nanoantennas.

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**Fig. 3 | High-contrast electrical switching of a metallic polymer metalens-on-demand.**

a) Setup to electrically switch a metalens. An electrochemical three-electrode setup is used to tune the applied voltage via cyclic voltammetry. The camera is placed in the focal plane of the metalens (focal length of f = 5 mm) to image the optical performance of the metalens. b) Camera images and cross-sectional intensity profiles in the focal plane of the metalens. Left: An applied voltage of −1 V switches the polymer insulating and thus the metalens OFF with no diffractive power. Right: A voltage of +1 V switches the polymer metallic and the metalens ON. A focus is observed. c) Time sequence of camera images showing the focused intensity by the polymer metalens while the applied voltage is switched via cyclic voltammetry between ±1 V (2 cycles). A video showing all frames and the cyclic voltammogram can be found in Movie S1 in the Supplementary Information. d) Normalized focused intensity by the polymer metalens as a function of the applied voltage during the switching cycles shown in (c). The scanning direction is marked with arrows. Non-volatile operation is possible at 0 V. The polymer metalens remains in the ON state at 0 V (set ON, marked green) when previously +1 V was applied. In contrast, it remains OFF at 0 V (set OFF, marked red) when previously −1 V was applied.
The results are depicted in Fig. 4a. We plot a cross-section of the metalenses as illustrated in Fig. 4b. The metaobjective is illuminated with a IR laser beam (λ = 2.65 μm) and the focused intensity is imaged along the optical axis. The metaobjective from metallic polymer allows for four different states. Non-volatile operation is used to set the refractive power of the individual metalenses either ON or OFF with an applied voltage of +1 V or −1 V, respectively. State 1 (metalens 1: ON, metalens 2: OFF): single focus at focal plane F1 of metalens 1. State 2 (metalens 1: OFF, metalens 2: ON): single focus at focal plane F2 of metalens 2. State 3 (metalens 1: OFF, metalens 2: ON): two foci at focal planes F1 and F2. State 4 (metalens 1: OFF, metalens 2: OFF): no refractive power of metaobjective. The entire metaobjective is thus switched OFF.

During the switching as well as irreversible reactions during electrochemical oxidation and reduction.

Due to the shown hysteresis in Fig. 3d, the metalens can either be set ON or set OFF at 0 V (marked in green and red) depending on the preceding applied voltage. Thus, an energy-efficient non-volatile operation is possible. The dwell time in the insulating OFF state after the external voltage has been turned off is 2–3 min until the polymer returns and relaxes into its pristine metallic state. Consequently, the dwell time in the metallic ON state is infinity as it is identical to the pristine state. This principle is used in the following to switch and set the states of a multi-functional metaobjective comprising two electrically switchable metallic polymer metalenses-on-demand.

The polymer metaobjective is sketched in Fig. 4a. As mentioned, it consists of two metalenses fabricated from metallic polymer, which are separately switchable. The focal lengths are f₁ = 6 mm for metalens 1 and f₂ = 5 mm for metalens 2 and they are spaced by 3.5 mm. Both metalenses comprise nanoantennas (L = 380 nm, W = 160 nm, H = 90 nm) resonant at λ = 2.65 μm, which is used as the laser illumination wavelength. The metalenses are mounted in the same electrochemical cell and their gap is filled with electrolyte (see Methods and Fig. S4 in the Supplementary Information). We use a non-volatile operation (as explained in Fig. 3d) to set the individual states of the two metallic polymer metalenses.

The metaobjective is switchable between four different states. The results are depicted in Fig. 4b. We plot a cross-section of the xz-plane which is obtained by moving the IR camera along the optical axis (z-direction). In the first state (top) metalens 1 is set ON (+1 V) whereas metalens 2 is set OFF (−1 V). Only metalens 1 focuses the incoming circularly polarized light beam and we find a single focus in the focal plane F₁ at position z = 6 mm. The second state (metalens 1: set OFF, metalens 2: set ON) switches the focal length of the metaobjective and we observe a single focal spot in the focal plane F₂ of metalens 2 at z = 8.5 mm. Furthermore, we realize two unusual states with our metallic polymer metaobjective. Switching both metalenses simultaneously ON via an applied voltage of +1 V creates a multi-focal metaobjective. We obtain focal spots in both focal planes F₁ and F₂. An applied voltage of −1 V to both polymer metalenses (bottom of Fig. 4b) sets both metalenses OFF and into the insulating state. The refractive power of the entire metaobjective is switched OFF and no focal spots are observed. It should be noted that in the ON/ON-state the focusing (conversion) efficiency of each metalens defines how the two metalenses in the metaobjective influence each other. For a low focusing efficiency, one obtains two foci (compare state 3 in Fig. 4b). In this case, the rear metalens will focus the non-converted circularly polarized light. Thus, the intensity of the rear focus depends on the converted intensity and thus focusing efficiency of the front metalens. Ultimately, for a conversion/focusing efficiency of 100%, the two foci in the ON/ON-state will vanish. Rather the rear metalens will convert and further focus (or collimate) the light coming from the front metalens. In this case, the metalenses would act similar to conventional lenses.

In conclusion, we have demonstrated electrically switchable high-contrast metalenses-on-demand and a multi-functional metaobjective by using the optical metal-to-insulator transition in metallic polymer nanoantennas. We observe an ON- and OFF-state of the metalenses, where their refractive power can be switched ON and OFF via an applied voltage of +1 V and −1 V, respectively. These low switching voltages are CMOS compatible and switching can be operated up to video rate frequencies of 33 Hz. Further improvements of the switching speed might be achievable, for example, by either changing the overall size of the nanoantennas (less material to be switched), by removing the SiO₂ cover on top of the nanoantennas (larger surface for electrolyte to access), or by using different electrolytes (e.g., smaller ions compared to TBAPF₆). By combining two metallic polymer metalenses into a metaobjective, four different states including a multi-focal state were demonstrated. In the future, several directions are possible which will allow to further push the integration of metallic polymer metasurfaces into electro-optical devices. For example, development in the material properties and fabrication processes will optimize and enhance the switching speeds, lifetime, and efficiency to meet the requirements of future display technologies. Mass producibility of the metalenses is possible, e.g., via nanoimprint-lithography (roll-to-roll) to meet the requirements in consumer-
based products. In AR/VR devices, our metalenses could specifically be used in the NIR or MIR for, e.g., eye-tracking devices, facial recognition, or to scan and create a 3D map of the surrounding, similar to future miniaturized LiDAR devices in autonomous cars. Furthermore, we aim at even higher charge carrier densities and thus shorter plasma wavelengths to enable switchable plasmonic operation in the telecom or even visible range. With these developments, even visible video-rate holograms for AR and VR applications should come in reach.

Methods
Spectral IR measurements
We use a Fourier-transform infrared (FTIR) spectroscopy setup (Bruker Vertex 80 spectrometer with Hyperion 3000 microscope) to measure the spectral response of the metallic polymer nanoantennas and metalenses. ITO-covered glass substrates are used as reference.

Electrochemical switching of metalenses/metaobjective
A home-built electrochemical (EC) cell with optical access is used to electrically switch the metallic polymer metalenses/metaobjective. The cell is sealed on the top and bottom with the samples (polymer metalenses on ITO-covered glass substrate) to facilitate measurements in transmission (see Figure S4 in the Supplementary Information). The EC cell is filled with an electrolyte (0.1 mol/l TBAFP, in acetonitrile). We use a three-electrode setup where the voltage is controlled via a potentiostat (BioLogic SP-200). The ITO layer (for electrical contacting) and the polymer metalenses/metaobjective serve as the working electrode. The counter electrode (platinum wire) and the reference electrode (silver/silver-chloride wire) are in direct contact with the electrolyte. The electrical wiring for the metaobjective comprising two polymer metalenses is explained and sketched in Fig. S4 in the Supplementary Information.

Please note that our concept is based on an electrochemical approach where the conducting electrolyte is uniquely chosen to oxidize and reduce our metallic polymer PEDOT:PSS at ±1 V. ITO will not show any redox reaction for this particular voltage range. Similarly, there will be no charge accumulation at the top surface of ITO, as the adjoining layers are electrically conducting, and a current is flowing through the electrochemical cell. A change of the optical properties of ITO via gating and charge accumulation occurs only in a MOS (metal-oxide-semiconductor) configuration, which means that the ITO (serving as ground) and the counter electrode (e.g., gold or aluminum layer) are separated by an insulating layer. Consequently, we do not expect the ITO to change its optical properties in our specific sample geometry.

Data availability
The authors declare that all data supporting this work are contained in graphics displayed in the main text or in the Supplementary Information. Data used to generate these graphics are available from the authors upon request.

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Author contributions
J.K., M.H., and H.G. conceived the project. J.K. and Y.L. designed the metalenses. J.K. and M.U. fabricated the samples. J.K. performed the measurements and carried out the data analysis. Y.L., M.F., and M.H. contributed to the experimental setup, sample fabrication, and measurements. H.G., M.H., and S.L. supervised the project. All authors discussed the results and contributed to the writing of the manuscript.

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Correspondence and requests for materials should be addressed to Julian Karst or Harald Giessen.

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