

Detecting DNA and RNA and Differentiating Single-Nucleotide Variations via Field-Effect Transistors

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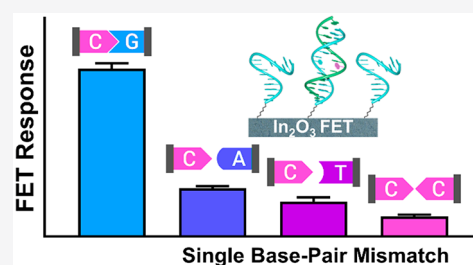
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ABSTRACT: We detect short oligonucleotides and distinguish between sequences that differ by a single base, using label-free, electronic field-effect transistors (FETs). Our sensing platform utilizes ultrathin-film indium oxide FETs chemically functionalized with single-stranded DNA (ssDNA). The ssDNA-functionalized semiconducting channels in FETs detect fully complementary DNA sequences and differentiate these sequences from those having different types and locations of single base-pair mismatches. Changes in charge associated with surface-bound ssDNA vs double-stranded DNA (dsDNA) alter FET channel conductance to enable detection due to differences in DNA duplex stability. We illustrate the capability of ssDNA-FETs to detect complementary RNA sequences and to distinguish from RNA sequences with single nucleotide variations. The development and implementation of electronic biosensors that rapidly and sensitively detect and differentiate oligonucleotides present new opportunities in the fields of disease diagnostics and precision medicine.

KEYWORDS: DNA, RNA, mismatch, polymorphism, SNP, SNV, FET, sensing, biosensor



Nucleic acid diagnostics have enabled many opportunities in modern medicine for the analysis, diagnosis, and treatment of genetic and infectious diseases.¹ The identification and subsequent detection of disease-associated nucleic acids are necessary for personalized and preventative medicine.¹ Moreover, the recent global pandemic of 2019, with the emergence of the novel coronavirus (COVID-19), illustrates the unmet need for rapid, flexible nucleic acid testing technology for disease diagnostics that is easily deployable, manufacturable, and adaptable to new infectious agents once novel genomes are sequenced and identified.^{2,3}

Single-nucleotide variations (SNVs) are important in both genomes and somatic mutations, such as in tumors, as they affect disease progression and therapeutic responses.⁴ Thus, significant interest and efforts are aimed at identifying common and rare SNVs, their patterns of occurrence and relationships with complex diseases, and biological traits. Detecting specific oligonucleotides and their variants rapidly in human populations and patient tissue samples will improve disease diagnostics and precision medicine.^{4–8} The identification of known variants and the discovery and association of new variants with diseases are both important.¹

Single-nucleotide polymorphisms (SNPs) are the most common form of genetic variation typically defined as SNVs occurring in at least 1% of the population.^{4–8} On average, SNPs occur every 1000 nucleotides in human genomes and contribute to individuality in humans and other organisms.^{4–10} Single-nucleotide polymorphisms are found in coding and

noncoding regions of DNA and in RNA (e.g., mRNA, tRNA, miRNA).^{11–16} Many SNPs have no discernible effects on health or development. Nonetheless, SNPs have been correlated with genetic susceptibility to asthma,¹⁷ Alzheimer's disease,¹⁸ β -thalassemia,¹⁹ sickle cell disease,²⁰ and cancers,^{14,21–24} as well as responses to xenobiotics.^{5,25}

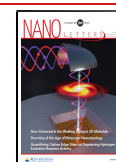
Commonly, SNVs are identified and profiled using techniques that require oligonucleotide amplification (i.e., polymerase chain reaction, PCR)⁴ and/or fluorophore-labeled oligonucleotides (e.g., molecular beacons, DNA microarrays).^{4,26,27} These methods are powerful in laboratory settings, yet are limited in terms of translation to clinical diagnostic and point-of-care applications. Electrochemical detection,²⁸ nanopore sequencing,²⁹ mass spectrometry,^{19,30} and high-performance liquid chromatography³¹ show promise for SNV detection. However, these techniques suffer from throughput issues, are complex, expensive, and labor-intensive, and often require nucleotide labeling and/or amplification.

Applications that necessitate analyzing large numbers of patient DNA or RNA samples, or multiple SNVs, highlight the benefits of developing sensor platforms capable of rapid, direct,

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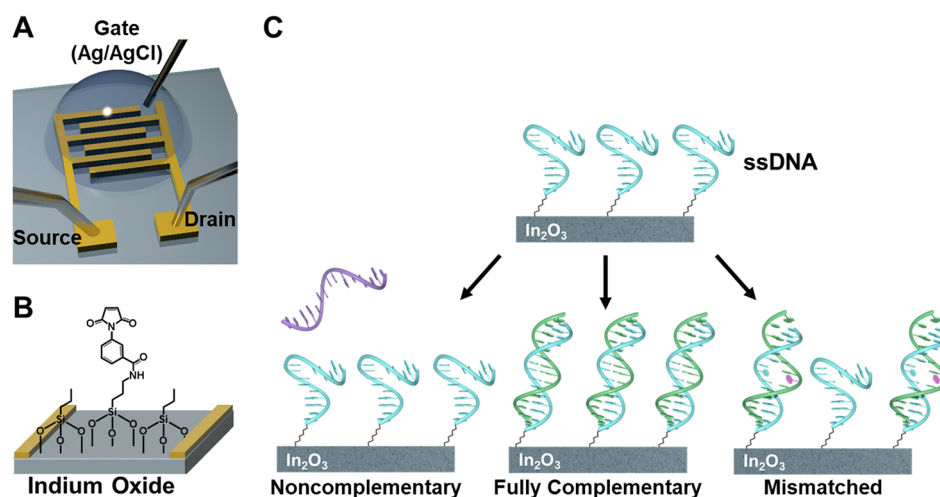


Figure 1. Oligonucleotide detection via field-effect transistors (FETs). (A) Transistors ($2 \times 3 \text{ mm}^2$) were composed of 4 nm thin-film In_2O_3 as the channel material, with 10 nm Ti adhesion and 30 nm top Au layers patterned as interdigitated electrodes. The FETs were operated in a solution-gated setup with a Ag/AgCl reference electrode as the gate electrode. (B) Thiolated single-stranded DNA (ssDNA) was tethered to amine-terminated silanes coassembled with methyl-terminated silanes on metal oxide surfaces using *m*-maleimidobenzoyl-*N*-hydroxysuccinimide ester as a linker. (C) Field-effect transistors functionalized with ssDNA were exposed to noncomplementary, fully complementary, or mismatched sequences.

multiplexed, and label-free SNV detection and read-out. Field-effect transistor (FET)-based biosensors have been used to identify and to quantify biological analytes wherein target binding is directly transduced into changes in FET conductance (electronic signals) for high-sensitivity detection.^{32–40} Transistor surfaces are modified with receptors (e.g., proteins, antibodies, and nucleic acids) to enable selective molecular recognition of a variety of targets ranging from small molecules^{32,33,40} to nucleic acids^{41–45} and proteins.^{46–48}

We present a strategy for detecting oligonucleotide sequences and SNVs using ultrathin-film quasi-2D metal oxide FETs. Previously, we demonstrated the use of these types of FETs for the sensitive and selective detection of a range of small molecules (e.g., neurotransmitters, amino acids, sugars, and lipids) in complex biological fluids.^{32,33,40} Here, we functionalize the semiconductor channel material of the FETs with ssDNA to detect complementary DNA hybridization. We distinguish FET responses associated with single base-pair mismatches of different types and positions to illustrate the potential for SNV genotyping. We hypothesize that sequence differentiation is contingent upon differences in duplex stability and, thus, the degree of DNA hybridization (i.e., surface density of dsDNA vs ssDNA). Further, we illustrate RNA detection and sequence differentiation at the single-base level. The capability to discriminate oligonucleotides that differ by a single base using thin-film metal oxide FETs is anticipated to enable the development of parallelized electronic arrays for rapid SNP genotyping and tissue or cellular transcriptomics.⁴⁹

A representative FET with the detection setup is shown in Figure 1A. Arrays of transistors were fabricated with ultrathin In_2O_3 (ca. 4 nm) deposited as the channel material using a high-throughput solution-processable sol–gel method.^{32,33,40,50,51} Thiolated ssDNA (probe) was functionalized on FET surfaces via attachment to self-assembled silanes on the indium oxide channels using an amine-thiol linker (Figure 1B).^{32,33} Individual ssDNA-functionalized FETs were exposed to solutions containing oligonucleotides (targets), and FET responses were measured over a period of 30 min (*vide infra*). Device responses were determined after exposure to targets that were noncomplementary, fully complementary, or

had single base-pair mismatches with respect to the probe sequences functionalized on FET surfaces (Figure 1C).

We exposed FETs to complementary vs noncomplementary DNA (Figure 2A). Calibrated responses were determined by

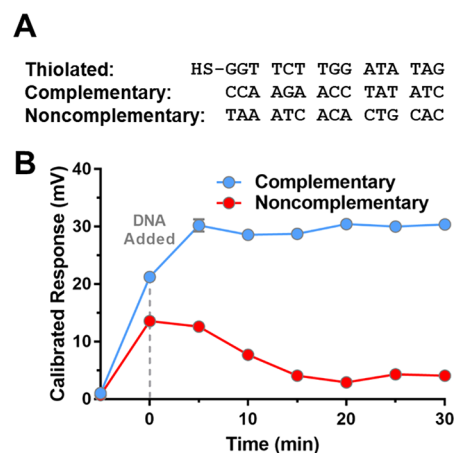


Figure 2. Temporal response of field-effect transistors (FETs) to DNA hybridization. (A) Sequences of DNA for FET measurements. (B) Responses of two representative FETs with respect to incubation time with solutions containing either fully complementary or noncomplementary sequences. The DNA solutions were added to FETs at 0 min. Responses associated with complementary sequences remained elevated, while responses to noncomplementary sequences showed initial increases followed by decreases in conductance, ultimately resulting in negligible changes in FET calibrated responses. Error bars, which are too small to be visualized in some cases, are standard errors of the means for $N = 5$ consecutive gate-voltage sweeps at each time point.

dividing baseline-subtracted current responses by the change in source-drain current with the voltage sweep to minimize device-to-device variation (see Supplemental Methods).⁵² The FETs incubated with target oligonucleotides complementary to ssDNA probe sequences on the In_2O_3 channel surfaces showed initial increases in conductance that stabilized over 30 min (Figure 2B). By contrast, FETs incubated with a non-

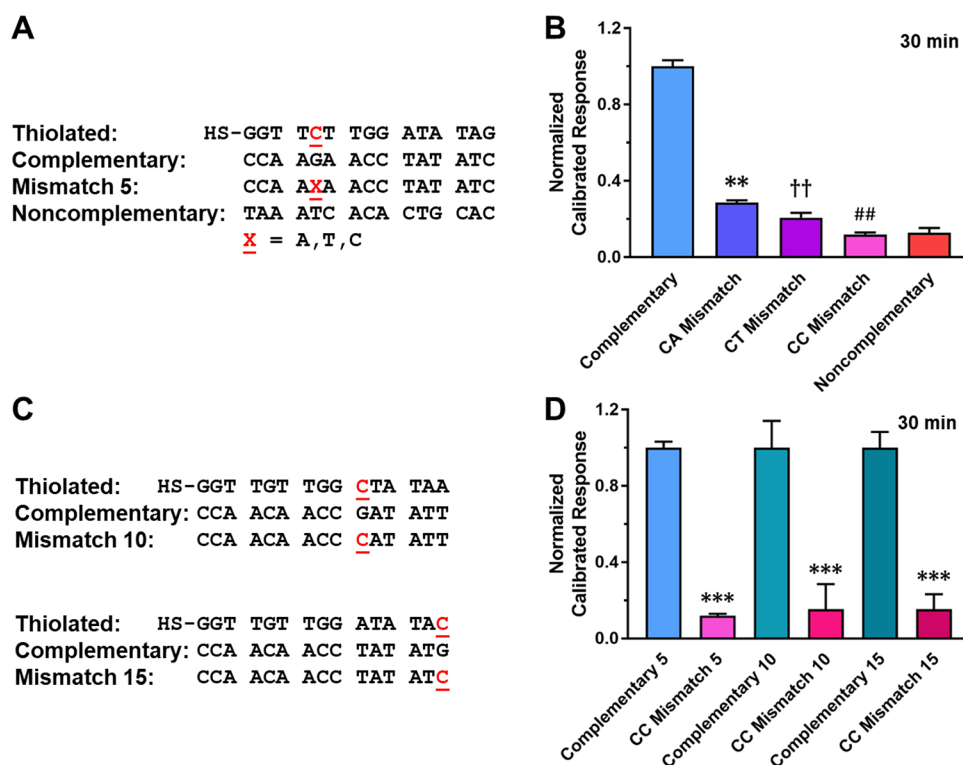


Figure 3. Discrimination of single-nucleotide variations. (A) Sequences of DNA used for field-effect transistor (FET) measurements with different types of mismatches at the 5th position from the attachment location. (B) Mean field-effect transistor (FET) responses after 30 min of target DNA exposure demonstrating discrimination of sequences with single base-pair mismatches. Error bars are standard errors of the means with $N = 3$ FETs/group. $**P < 0.01$ vs complementary, CT, CC, and noncomplementary, $\dagger\dagger P < 0.01$ vs complementary, CA, CC, and noncomplementary, $##P < 0.01$ vs complementary, CA, and CT. (C) Sequences of DNA for FET measurements with the same mismatch at the 10th or 15th position from the attachment location. (D) Mean FET responses after 30 min of target DNA incubation differentiating sequences with a CC mismatch at the 5th, 10th, or 15th position. Error bars are standard errors of the means with $N = 3$ FETs/group. $***P < 0.001$ vs the corresponding fully complementary DNA. Data for complementary and CC mismatched sequences at the 5th position are reproduced from panel B for comparison.

complementary sequence showed an initial increase that returned to near baseline over time. We attribute divergent behavior following response stabilization to differences in DNA hybridization. In the case of fully complementary target DNA, hybridization produced increases in stabilized FET calibrated responses over a range of target concentrations (Figure S1), whereas a lack of hybridization for noncomplementary sequences resulted in minimal conductance change after stabilization (e.g., 30 min) (Figure 2B).

Sensor responses were then determined after exposing ssDNA-functionalized FETs to DNA oligonucleotides with different single base-pair mismatches (i.e., CA, CT, CC) at the fifth position distal to the thiolate attachment (Figure 3A). Target sequences were designed to be short (i.e., 15-mers), as single base-pair mismatches are more destabilizing in shorter duplexes.⁵³ Similar to fully complementary and noncomplementary responses, sensor responses associated with mismatched sequences stabilized after 20–30 min of incubation (Figures S2 and S3). Responses at 30 min post-DNA addition were averaged over all measurements. In all cases, FETs exposed to mismatched DNA sequences had significantly lower calibrated responses compared to FETs exposed to fully complementary target DNA (Figure 3B). Thus, sensors distinguished DNA sequences that differed by a single base compared to the fully complementary sequence. Moreover, mean sensor responses for the various fifth position mismatches differed significantly from one another (Figure

3B), demonstrating that sensor responses discriminated sequences with different types of single base-pair mismatches.

In addition to DNA sequences with different single-base alterations at the same position, the responses of ssDNA-functionalized FETs to sequences with the same mismatch at different positions along the target strand were determined (Figure 3C). Time responses (Figure S4A,B) were comparable to those for mismatches involving different nucleotides at the same position and noncomplementary DNA (Figure S2). Sensors exposed to targets with CC mismatches at the fifth, 10th, or 15th positions from the thiolate attachment showed greatly reduced responses compared to those of the analogous fully complementary sequence (Figure 3D). The ability to distinguish sequences that differ with respect to mismatch distance from FET surfaces illustrates that oligonucleotides that differ by as little as a single nucleotide, regardless of position, are differentiated from perfectly matched complementary sequences. Here again, minimal responses to noncomplementary sequences were observed (Figure S4C,D).

The transfer characteristics (I – V curves) of ssDNA-FETs after incubation with complementary DNA showed reductions in current with respect to time (Figures S5A and S6A). Two competing effects associated with hybridization are hypothesized to contribute to changes in FET conductance. (1) Negative charge near FET surfaces increases after duplex formation because one negative charge is added per base in the hybridized strand. (2) By contrast, negative charge near FET surfaces decreases after duplex formation due to the increased

stiffness of double-stranded vs single-stranded DNA. Hybridization increases the radius of gyration of DNA (i.e., DNA is extended from ca. 1.5 nm for ssDNA to 5 nm for dsDNA for the sequences investigated).⁵⁴ We conclude the former effect dominates since the direction of change in FET conductance indicates a net increase in negative charge close to FET surfaces.

The transfer characteristics observed here are consistent with our previous findings showing that changes in FET transfer characteristics (i.e., decreases in current) for *n*-type In₂O₃ semiconductor materials are predominantly due to gating (i.e., band bending)⁵⁵ associated with negatively charged DNA backbones.^{33,40} Moreover, as per our previous work with aptamer-based FET sensors, the directions of change of the *I*–*V* curves in Figures S5 and S6 indicate the accumulation of net negative surface charge and electrostatic repulsion of semiconductor charge carriers, consistent with DNA hybridization. Unlike in one of our earlier studies in which ssDNA was inserted into defects in well-formed self-assembled alkanethiol monolayers on Au,⁵⁶ ssDNA functionalized via silane chemistry on semiconductor channels in FETs is likely to be disorganized, and dsDNA may lay across surfaces, which would increase the gating effect associated with DNA hybridization.

A return to baseline was observed after initial current changes for noncomplementary and mismatched DNA incubation (Figures S5B,C and S6B,C). Initial increases in FET calibrated responses (decreases in current) after DNA addition are due to the introduction of solutions containing negatively charged DNA near FET surfaces, as well as perturbation of FET surfaces due to mixing sample solutions physically during DNA addition. The return to baseline implies little to no hybridization (i.e., minimal accumulation of negative charge near FET surfaces) for noncomplementary and mismatched sequences with respect to time.

To investigate the contributions of duplex stability to DNA detection via ssDNA-FETs, DNA melting curves were determined for sequences with mismatches at the fifth position from the thiolate modification vs the fully complementary target (Figure 4A). The temperature at which dsDNA dehybridizes (i.e., melts) is indicative of the stability of hybridized oligonucleotides; more stable duplexes have higher melting temperatures.^{57–59} The melt curves indicated that the duplex with the CC mismatch had the lowest melting temperature (i.e., lowest stability), followed by the duplex with the CT mismatch, and then the CA mismatch. The melting temperature for the fully complementary duplex was ~10 °C higher than for the mismatched duplexes. Sequences with CC mismatches at different positions similarly showed reduced melting temperatures compared to the fully complementary duplex (Figure S7).

The FET responses for various duplexes and the corresponding melting temperatures were highly correlated ($R^2 > 0.99$; Figure 4B), suggesting that FET responses are associated with the relative stabilities of the hybridized DNA sequences. These results are consistent with the hypothesis that DNA detection via ssDNA-FETs is based on dynamic equilibria, wherein duplex stability is related to the probability of hybridization and, thus, greater negative charge near FET surfaces. Mismatched DNA sequences, which are thermodynamically less stable (i.e., have lower melting temperatures), are statistically less likely to be hybridized with surface-tethered ssDNA probes, leading to attenuated accumulation of surface

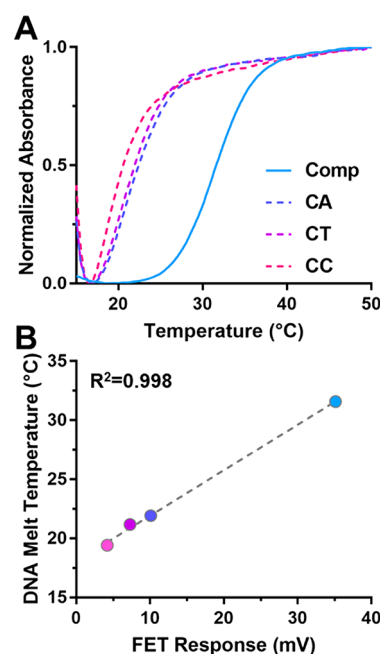


Figure 4. DNA melting-curve analysis. (A) DNA melting curves for dehybridization of sequences in Figure 3A show the relative stabilities of different mismatches vs fully complementary hybridization. (B) Correlation of field-effect transistor (FET) calibrated responses to different sequences from Figure 3B vs melting temperatures. The linearity index (R^2) is indicated. Symbol colors are as defined in panel A.

negative charge and lower measured FET responses. Rinsing of FET surfaces after 30 min of DNA incubation produced a decreased response for the noncomplementary sequence vs a minimal change for complementary and CC mismatched sequences (Figure S8), suggesting that small FET responses arising from noncomplementary DNA are largely due to nonspecific adsorption.

To investigate whether our approach can be used to detect RNA, we tested ssDNA-functionalized thin-film In₂O₃ FETs with complementary, (CC) mismatched, and noncomplementary RNA sequences (Figure 5A). Detection of RNA is important in testing for the presence of diseases, such as infection by RNA viruses.³ Furthermore, single-nucleotide polymorphisms occur in RNA (*vide supra*), and similar to SNVs in DNA, have important implications in genetic diseases.^{11–14} Genotyping SNVs in RNA could be advantageous for applications such as noninvasive prenatal diagnostics, where placental RNA can be obtained from maternal plasma samples.¹² Notably, DNA–RNA duplexes adopt an A-form helical conformation compared to the B-form helix typical of dsDNA.⁶⁰ Significant FET calibrated responses were observed only in the case of the fully complementary RNA sequence; mismatched and noncomplementary sequences produced negligible changes in FET responses (Figure 5B).

In sum, we illustrate the use of a platform for electronic, sequence-specific detection of DNA and RNA. Oligonucleotides that differed by only a single base were readily distinguishable using solution-processable ultrathin-film metal oxide FET sensors. The detection and discrimination of single base-pair mismatches in dsDNA and RNA–DNA duplexes illustrates the potential of this platform for label-free, electronic SNV genotyping. To detect specific SNVs, different FETs functionalized with different probe sequences would be

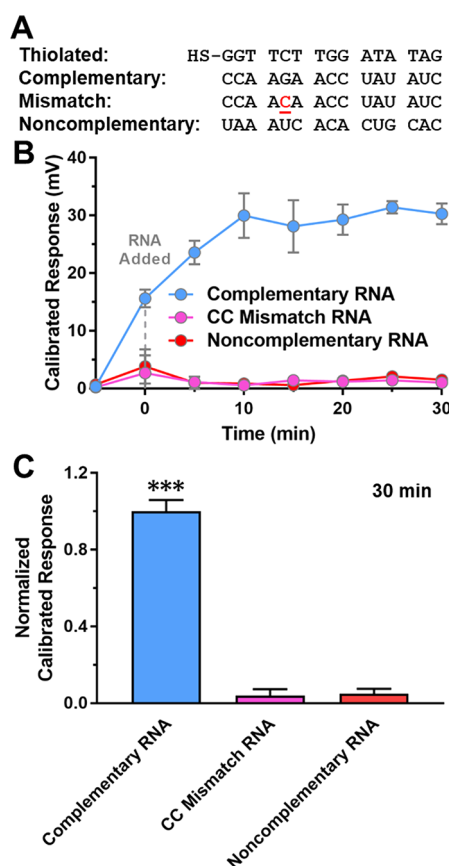


Figure 5. Sequence-specific RNA detection. (A) Sequences of RNA used for field-effect transistor (FET) measurements. (B) Representative DNA-functionalized field-effect transistor (FET) responses with respect to time after incubation with RNA. Calibrated responses to complementary sequences increased and remained stable over time, while responses to noncomplementary and mismatched sequences were negligible. Error bars, which are too small to be visualized in some cases, are standard errors of the means for $N = 5$ consecutive gate-voltage sweeps at each time point for a single representative FET per condition. (C) Mean FET responses after 30 min of RNA incubation demonstrating differentiation of complementary RNA vs CC mismatched and noncomplementary RNA. Error bars are standard errors of the means with $N = 2$ FETs/group. *** $P < 0.001$ vs CC mismatch and noncomplementary RNA.

fabricated in sensor arrays.⁶¹ The fabrication methods used here are well suited to produce FET arrays.^{32,40,50,62–64} Using two FETs as an example, one functionalized with ssDNA fully complementary to the SNV major allele and the other functionalized with ssDNA fully complementary to the corresponding minor allele, DNA (or RNA) samples from homozygous major or minor allele carriers or hemizygous individuals could be straightforwardly differentiated (i.e., genotyped).

We posit that the mechanism of our ssDNA-FET platform is based on the detection of differences in the extent of nucleic acid hybridization near the surfaces of transistors. Based on this detection method, the platform is not limited to the sequences investigated here; we expect that any nucleic acid sequence, including those with variations, single nucleotide or otherwise, that result in reduced hybridization stability compared to the fully complementary sequence, could be detected and discriminated.

Longer ssDNA sequences can be tethered to FET surfaces for the detection of multiple mismatches along the same sequence.⁶⁵ Additionally, modulating the ionic strength of the sensing solution changes the charge screening distance near FET semiconducting channels (i.e., the Debye length), thus changing the (distance) range of sensitivity of the sensor.^{33,40} The latter parameter suggests a strategy for screening SNVs that are closer to or further away from FET channels. Experiments comparing the gating associated with shorter complementary sequences vs longer complementary sequences will help to elucidate the contributions of charge vs change in radius of gyration to specific FET responses. Functionalizing arrays of FETs addressed with different ssDNA sequences that are perfect matches to different SNVs and their alleles will enable rapid profiling of DNA or RNA from tissues or cells, as well as detection of other types of nucleotide mutations (e.g., using wild-card bases).⁶⁶

Previously, FETs functionalized with ssDNA, or sometimes single-stranded peptide nucleic acids,^{67,68} have been used to detect DNA with specific sequences.^{61,69–73} Such FET sensors have been demonstrated for real-time^{68,74–76} and ultrasensitive detection of DNA (i.e., pico- to nanomolar detection limits).^{69,73} Strategies employing FET sensors for the measurement of mismatched DNA sequences (e.g., DNA strand displacement,⁶⁹ DNA nanotweezers⁷⁷) have been developed toward electronic SNV detection.^{67,78} Many FET platforms for DNA detection involve the use of one- or two-dimensional materials (e.g., graphene,^{44,48,69,75} graphene oxide,⁷⁶ carbon nanotubes,³⁵ semiconductor nanowires⁷⁹) as channel materials. These materials maximize FET surface-to-volume ratios, presumably increasing device sensitivities.⁴³ However, these materials entail challenges associated with synthesis, material heterogeneity, device reproducibility, and robust functionalization.^{38,80,81}

Compared with other FET-based detection platforms, our functionalized transistors can be straightforwardly and reproducibly fabricated at the wafer scale in arrays using soft-lithographic techniques,^{32,50,62–64,82,83} increasing the potential for rapid translation and deployment toward screening for pandemic infection, clinical disease diagnostics, and personalized healthcare applications.⁸⁴ In contrast to FETs based on 2D materials, solution-processed ultrathin indium oxide films are highly uniform,^{32,51,85} can be straightforwardly and selectively functionalized,^{33,86} and have been demonstrated to have higher device sensitivities and lower detection limits in potentiometric biosensing applications (e.g., pH and glucose sensing) compared with other 2D (e.g., graphene, reduced graphene oxide, MoS₂) and 1D (e.g., carbon nanotube, Si nanowire) materials.⁵¹ Moreover, device architectures and performance can be tailored for specific applications (i.e., nanostructuring),^{32,50,87} and ssDNA surface densities can be altered to tune FET responses.³³ Ultimately, testing of clinical samples (e.g., nasal swabs, serum, biobanked tissue samples) will be needed for platform validation. Even so, the ssDNA-FETs investigated here exemplify rapid, label-free, unamplified sequence-specific DNA and RNA detection with broad implications in screening and in precision medicine.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.0c01971>.

Experimental methods and a FET concentration experiment, time responses, I - V curves, noncomplementary controls, DNA melting curves, rinse experiment, and statistical methods and table (PDF)

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Author Contributions

All authors designed the experiments. K.M.C., J.M.A., N.N., and B.Z. carried out the experiments. All authors performed data analysis and interpreted the results. K.M.C., A.M.A., and P.S.W. wrote the manuscript with input from all authors.

Notes

The authors declare the following competing financial interest(s): K.M.C., A.M.A., and P.S.W. have filed an international patent application on detecting and discriminating nucleic acid sequences using FETs, International application PCT/US2019/027080.

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