Surface acoustic wave (SAW) devices are commonly used in communication and signal processing.\(^1\) Recently, SAW devices are also employed in wide area network, wireless local area network communications, wireless passive identifications tags,\(^2\) various sensors,\(^3\)\(^-\)6 and RF front-end for mobile communications.\(^7\)\(^-\)8 In a conventional SAW device, SAW frequency is determined by the acoustic velocity of the substrate material, and the acoustic wavelength determined by the IDT design. Therefore, it has a fixed operating frequency without agility. However, many modern communication systems require multi-band and multi-mode capability for signal transmitting and receiving. With increasing demands for advanced wireless communication, such as IoT (Internet of Things), it is not practical to simply add more filters. Frequency tunable devices, such as adaptive filters, can process multi-channel signals, extend the operating bandwidth, and reduce the architecture complexity. Furthermore, tunability in the time or frequency response domain allows a reconfigurable system to smartly adapt to its operating environment.

Tunable SAW devices are usually achieved through three different approaches: wavelength selection, perturbation of piezoelectric material properties, and perturbation of SAW boundary conditions. Wavelength selection is often referred as a filter bank, which provides frequency variations through switching between selectable IDTs. However, such “tuning” is not continuous due to the discrete switching among filters. Furthermore, the resulting large device area essentially excludes its applications in compact mobile systems. The perturbation of piezoelectric material properties, such as stiffness coefficient, usually requires a high external magnetic or electric field\(^9\) to achieve a very small frequency variation. In comparison with the above two techniques, the SAW boundary condition tuning method using a piezoelectric-semiconductor dual layer structure requires a smaller biasing voltage as it only affects a thin layer of semiconductor material.\(^11\)\(^-\)13

We previously demonstrated a voltage-controlled frequency tunable SAW device through the acoustoelectric interaction in a piezoelectric-semiconducting dual layer, consisting of a piezoelectric ZnO SAW device integrated with an n-ZnO/GaN heterostructure.\(^14\) The piezoelectric ZnO/GaN layer structure provides high-frequency SAW response (1.25 GHz), and the interaction between the SAW generated electric field in the piezoelectric layer and the free carriers in the semiconducting layer resulted in 0.9\% frequency change, equivalent to a frequency change of 11.2 MHz at \(-25\) V bias. Although this device design improved the frequency tunability and reduced operation voltage compared with other published tunable SAW devices, it still contained some additional loss mechanisms which increased overall power consumption. For instance, the n-ZnO layer directly under IDT does not contribute to SAW tuning. Adversely, this layer would provide an electron leakage path, thus reducing the energy transfer efficiency between the electrical signal and the mechanical wave. To increase the energy efficiency of voltage tunable SAW device and improve the electromechanical coupling coefficient \(K^\text{s}\), a better device structure and process design is needed.

In this work, we report a new design of the voltage controlled SAW phase shifter based on the exposed IDTs configuration compared with previous exposed IDT. The buried IDTs are sandwiched by GaN and piezoelectric ZNO layer, instead of being exposed to air, to improve the acoustic coupling. The n-ZnO layer under IDT region is removed to reduce the energy loss during SAW generation. The tunability and attenuation of two devices are compared, showing a superior performance of buried IDT configuration.

### Device Structure and Material Properties

Schematic drawings of the tunable SAW devices with exposed and buried IDT configurations are presented in Figs. 1a and 1b, respectively. The device layer structures of both configurations follow the same order from top to bottom: Au/Ti/NZNO/n-ZnO/GaN/Al2O3. The core functional structure of the device is based on a piezoelectric NZO layer on the semiconductor NZO/GaN heterostructure for frequency tuning. Zinc oxide (ZnO) and gallium nitride (GaN) are both wide bandgap semiconductors and belong to the same wurtzite crystal structure group with close lattice parameters. High-quality, high resistivity piezoelectric ZNO films can be obtained by RF sputtering.\(^15\) In general, in a multilayerpiezoelectric material system where a low
along the longitudinal propagation direction as well as the transverse components in both vertical and horizontal shear directions. ZnO films grown on high-velocity and low-loss substrates such as GaN generate higher-order generalized SAW modes; therefore integration of a piezoelectric ZnO with GaN offers higher-order overtone SAW modes with high acoustic velocity and thus high frequency, as well as a high electromechanical coupling coefficient. The thickness of NZO and the IDT period \( P \) are optimized to be 0.8 \( \mu \)m and 6 \( \mu \)m to achieve high-order SAW modes, and therefore high-frequency SAW operation.

X-ray diffraction (XRD) analysis was carried out to characterize the crystalline property of NZO layer, using a PANalytical X’Pert3 Powder System with Cu Kα radiation (\( \lambda = 0.1540562 \) nm) as shown in Fig. 1c. The (0002) ZnO and (0002) GaN peaks are clearly defined, showing the preferred orientation of NZO along the c-axis. Fig. 1d shows the field emission scanning electron microscopy (FE-SEM, Hitachi S-800) image of overall Au (100 nm)/Ti (50 nm)/NZO (0.8 \( \mu \)m)/n-ZnO (50 nm)/GaN (4 \( \mu \)m)/Al\(_2\)O\(_3\) structure. The inset of Fig. 1d shows a high magnification transmission electron microscopy (TEM) image of the n-ZnO/GaN interface using JEOL 2100F transmission electron microscope that indicates the excellent crystal quality and the sharp and flat interface, benefiting low loss and high coupling SAW performances.

### Device Fabrication

The fabrication process flow chart of the tunable SAW device with exposed and buried IDT configuration is schematically presented in Figs. 2a and 2b, respectively. Both devices started with a 4-\( \mu \)m-thick n-type GaN (\( n = 6 \times 10^{16} \text{cm}^{-3} \)) deposited on a c-Al\(_2\)O\(_3\) substrate using metal-organic chemical vapor deposition (MOCVD). A 50 nm thick n-type semiconductor ZnO layer (n-ZnO) with a carrier concentration of \( 10^{17} \text{cm}^{-3} \) was then grown on the GaN layer by MOCVD at \( \sim 500 \) °C using DEZn (diethyl zinc), O\(_2\), and Ar as the precursor, oxidizer, and carrier gas, respectively. For exposed IDT structure shown in Fig. 2a, the Ni-doped ZnO layer (0.8 \( \mu \)m) was directly deposited on n-ZnO by RF sputtering (NZO target: 5 at. \% Ni). The deposition was carried out in an ambient mixture of Ar and O\(_2\) (1:3), and the overall chamber pressure was maintained at \( 8 \times 10^{-3} \) Torr. A Ti/Au (100 nm/50 nm) metal stack was deposited by electron beam evaporation and then patterned as the top gate using a photore sist (PR) lift-off process. Finally, the IDT electrodes were formed by depositing 150 nm thick Al followed by a selective wet etching process. For the buried IDT configuration shown in Fig. 2b, the basic process was essentially same, except that the n-ZnO layer was patterned by wet etching using diluted HCl solution (1:2000). Cr (50 nm) was then deposited by E-beam evaporation and followed by IDT patterning. The NZO (0.8 \( \mu \)m) was finally deposited on n-ZnO as well as on the IDTs electrodes.

### SAW Characteristics and Frequency Tunability

The electromechanical coupling coefficient \( k^2 \) of a SAW device pertains to the magnitude of the signal propagation loss accrued from

---

**Table 1. Material Constants for ZnO and GaN.**

| Symbol | ZnO | GaN |
|--------|-----|-----|
| Crystal Structure | wurtzite (hexagonal, 6 nm) | | |
| Lattice Parameter [nm] | a: 0.3243 | 0.3189 |
| | c: 5.206 | 5.185 |
| Piezoelectric Constant [C/m²] | \( e_{33} \): -0.51 | -0.2 |
| | \( e_{31} \): 1.22 | 0.29 |
| Relative Dielectric Permittivity | \( e_{31} \): 7.57 | 9.5 |
| | \( e_{33} \): 9.03 | 10.4 |
| Spontaneous polarization [C/m²] | \( P_{sp} \): -0.057 | -0.034 |
| SAW velocity [km/s] | \( \upsilon \): 3.3 | 6 |
| Piezo coupling coefficient | \( k^2 \): 11% | Up to 4.3% |

---

Figure 1. The schematic cross-section of the tunable SAW device with (a) exposed and (b) buried IDT configuration. (c) XRD scan for n-ZnO/NZO has grown on an Al\(_2\)O\(_3\)/GaN template; (d) SEM image of overall Au/Ti/NZO/n-ZnO/GaN/Al\(_2\)O\(_3\) structure. Inset: TEM image of n-ZnO/GaN interface.

---

**Lattice Parameter [nm]**

- ZnO: 3.243
- GaN: 5.206

**Piezoelectric Constant [C/m²]**

- ZnO: \( e_{33} \): -0.51
- GaN: -0.2

**Relative Dielectric Permittivity**

- ZnO: \( e_{31} \): 1.22
- GaN: 0.29

**Spontaneous polarization [C/m²]**

- ZnO: \( P_{sp} \): -0.057
- GaN: -0.034

**SAW velocity [km/s]**

- ZnO: \( \upsilon \): 3.3
- GaN: 6

**Piezo coupling coefficient \( k^2 \)**

- ZnO: 11%
- GaN: Up to 4.3%
input to output, which directly affects the insertion loss and effective bandwidth of a SAW device. Therefore, it is important to correlate the reduction of the insertion loss with the effective electromechanical coupling coefficient $K^2$ of the SAW devices with buried IDT configuration. The simulation using the multilayer transfer matrix model (TMM)\textsuperscript{10,21} is conducted in the ZnO/GaN/Al$_2$O$_3$ system for both of the exposed IDT and buried IDT configurations. The GaN and ZnO thickness is set to be 4 $\mu$m and 0.8 $\mu$m, respectively. The values of $K^2$ of SAWs are calculated using:

$$K^2 = 2 \frac{v_{oc} - v_{sc}}{v_{oc}}$$ \text{[1]}$$

where $v_{oc}$ is the acoustic velocity of the propagating SAW under free surface (when the semiconductor layer is fully depleted), and $v_{sc}$ is the acoustic velocity of the propagating SAW at electrically shorted conditions (when the semiconductor layer is undepleted). The $v_{oc}$ and $v_{sc}$ were calculated for a range of frequencies using the corresponding free surface and electrically shorted boundary conditions to obtain two dispersion functions $v_{oc}(hf)$ and $v_{sc}(hf)$, where $h$ is the total piezo layer thickness and $f$ is the frequency. The value of $K^2$ as a function of product $hf$ is then determined from Eq. 1.

The NZO/ZnO/GaN layer structure enables multiple surface acoustic waves: a base mode and three higher-order wave modes (HOWM).\textsuperscript{13} TMM simulation has been carried out using different NZO layer thickness (0.4 $\mu$m, 0.8 $\mu$m, 1.5 $\mu$m) based on exposed IDT structure, as depicted in Figs. 3a–3c. For high-frequency tunable device operation, there are two features of the $K^2$ vs. $hf$ curves should be considered: the maximum $K^2$ value at high frequency and wide effective bandwidth. For 0.4 $\mu$m NZO case, $K^2$ value of 4% can be only maintained within a small $hf$ product range of (2250 m/s – 3250 m/s), corresponding to the frequency range of (511.4 MHz – 738.6 MHz). With the NZO thickness increases to 0.8 $\mu$m, the $K^2$ is improved, and the $hf$ range of 4% $K^2$ significantly enlarges to (2650 m/s – 6420 m/s), corresponding to the frequency range of (552.1 MHz – 1337.5 MHz).

Figure 2. The schematic diagram of the NZO/ZnO/GaN-based tunable SAW devices process flow chart with (a) exposed IDT, and (b) buried IDT.
Figure 3. TMM simulation results of electromechanical coefficient $K^2$ of the NZO/n-ZnO/GaN SAW devices with exposed and buried IDT structure: (a) 0.4 μm NZO with exposed IDTs; (b) 0.8 μm NZO with exposed IDT; (c) 1.5 μm NZO with exposed IDT; (d) 0.8 μm NZO with buried IDT.

Further increasing of NZO thickness does improve the maximum $K^2$ at the lower frequency end. However, no major impact was observed on the overall frequency range (2660 m/s – 6480 m/s). Adversely, due to the increased film thickness, the frequency range shifts to (483.6 MHz–1178.2 MHz). The simulation of three different NZO layer thickness demonstrates that 0.8 μm is an optimized condition that provides both high-frequency operation and high $K^2$.

To analyze the effect of buried IDT, $K^2$ of the SAW device with buried IDT and 0.8 μm NZO layer is evaluated, as shown in Fig. 3d. Benefited from the unique dispersive properties in the ZnO/GaN heterostructure, buried IDT also possesses the high order wave mode at GHz frequency with a good effective coupling coefficient. Compared with Fig. 3b, overall the buried IDT structure has a higher $K^2$ value over the exposed IDT structure. For example, the 3rd HOWM of the device with exposed IDT holds a $\sim$4% $K^2$ value. However, the device with buried IDT presents a $K^2$ value of $\sim$5%, resulted from the improved electromechanical coupling, which is desired for SAW tuning. Moreover, the buried IDT configuration has a wider bandwidth and also shifts to a slightly higher $hf$ range (2830 m/s–6900 m/s) compared to the exposed IDT (2660 m/s–6420 m/s). As summarized in Table II, using 0.8 μm NZO layer as piezoelectric material in exposed IDT configuration, the highest frequency to sustain 4% $K^2$ is 1337.5 MHz. However, in buried IDT structure, the bandwidth value increases to 1568.2 MHz for an even higher $K^2$ (5%).

The transmission parameter $S_{21}$ of SAW is measured using an HP 8753D network analyzer and Cascade Microtech probes. The measured response around the center frequency of tunable SAW with both exposed and buried IDT, under 0 V gate bias voltage, are shown in Fig. 4. The measured 3rd HWOM corresponds to the SAW mode at which the device operated at a frequency of 1.25 GHz and 1.35 GHz for the exposed and buried IDTs, respectively, which confirms the simulations results in Figs. 3b and 3d. The background noise and peak intensity of exposed IDT is $\sim$31 dB and $\sim$18 dB. Through buried IDT structure, the background noise level reduces to $\sim$60 dB and signal peak increases to $\sim$13 dB. The signal to noise ratio is significantly improved due to the reduced loss by adapting buried IDT. In original exposed IDT design, besides the intentionally induced n-ZnO layer under gate area for tuning purpose, there are two additionally loss mechanisms.

DURING SAW generation, the voltage difference applied on neighboring IDT fingers creates a separated charge distribution on both top and bottom sides of a piezoelectric material. However, with the n-ZnO existing under piezoelectric layer, the charges at the bottom would recombine and convert energy into the ohmic loss. The portion of this n-ZnO layer that is under the IDT has no function in acoustic velocity tuning, but reduces the SAW intensity. The second loss is caused by Ti/Au top electrode which is placed directly on the propagation path of the SAW. This layer also causes ohmic losses. By using buried IDT process, the unnecessary n-ZnO layer could be removed without any process challenges and thus reduces the SAW generation related loss. With IDT being moved down to n-ZnO layer, the top metal gate is 0.8 μm away from the acoustic wave propagation surface; it reduces the ohmic loss from Au/Ti pad in the exposed IDT structure. Also, because the IDTs are brought close to the GaN layer, a larger portion of the acoustic wave will penetrate GaN film, thus increasing the SAW velocity and frequency. As a result, the 3rd HWOM in the device

---

**Table II. Simulated frequency range for 3rd HOWM using various IDT configurations and NZO thickness.**

| IDT configuration | NZO layer thickness (μm) | Total piezo thickness (μm) | 3rd HOWM simulated $K^2$ (MHz) | $f_{\text{min}}$ (MHz) | $f_{\text{max}}$ (MHz) |
|------------------|--------------------------|----------------------------|------------------------------|------------------------|------------------------|
| Exposed          | 0.4                      | 4.4                        | $>4\%$                      | 511.4                  | 738.6                  |
| Exposed          | 0.8                      | 4.8                        | $>4\%$                      | 552.1                  | 1337.5                 |
| Exposed          | 1.5                      | 5.5                        | $>4\%$                      | 483.6                  | 1178.2                 |
| Buried           | 0.8                      | 4.8                        | $>5\%$                      | 643.2                  | 1568.2                 |

---
with buried IDT holds a center frequency of 1.35 GHz, as opposed to 1.25 GHz for exposed IDT.

We utilized the acousto-electric effect as the mechanism of our device’s tunability. In a piezoelectric/semiconducting dual layer system, the electric field associated with the SAW propagation along a piezoelectric layer would couple with the mobile carriers existing in the semiconducting layer with a sheet conductivity \( \sigma \), causing SAW attenuation and velocity change. As the semiconductor thickness in the dual-layer structure is much smaller than the acoustic wavelength, the velocity change ratio \( \Delta v/v \) and attenuation coefficient \( \Gamma \) can be written as

\[
\frac{\Delta v}{v} = \frac{K_{\text{eff}}^2}{2} \frac{1}{1 + (\sigma_d/\sigma_M)^2},
\]

\[
\Gamma = k \frac{K_{\text{eff}}^2 (\sigma_d/\sigma_M)}{2} \left(1 + (\sigma_d/\sigma_M)^2\right)^2,
\]

where \( K_{\text{eff}} \) denotes the effective electromechanical coupling coefficient of the device, \( \sigma_M \) is the relaxation conductivity at which the maximum attenuation occurs, provided by \( \sigma_M = \nu_m (\epsilon_p + \epsilon_s) \), \( \epsilon_p \) and \( \epsilon_s \) are the dielectric constants of the piezoelectric and semiconducting layer, respectively. The term \( k = 2\pi/\lambda \) is the SAW wave vector. In our device, the modulation of the acoustic velocity due to the acousto-electric effect is contained within the delay line area. As the acoustic velocity is changed, the propagating SAW waves will accumulate time delays that can be measured as phase shifts. The phase shifts corresponding to the highest order wave mode of the devices with exposed and buried IDT configurations are measured under different dc bias voltages. The velocity shift ratio \( \Delta v/v \) is experimentally determined using the relation

\[
\frac{\Delta v}{v} = \frac{\lambda}{L_{\text{delay}}} \frac{\Delta \phi}{360}.
\]

where \( \Delta \phi \) is the bias induced SAW phase shift, \( \lambda \) is the SAW wavelength, \( L_{\text{delay}} \) is the delay line defined by edge-to-edge distance between IDTs. Eq. 4 gives the measure of the tunability range of the device.

Fig. 5a presents the acoustic velocity tunability \( \Delta v/v \) (normalized velocity change) of the NZO/ZnO/GaN-based SAW devices with exposed and buried IDTs as a function of gate bias, calculated from the device phase shifts using Eq. 4. In both configurations, all layer thicknesses are kept the same except the IDTs’ position in the structure. The tunability of the SAW device increases continuously toward negative gate bias voltages due to the depletion of the charges in the n-ZnO/GaN heterostructure interface and the charges of the free carrier in the n-ZnO layer. The maximum normalized frequency changes \( \Delta v/v \) reaches close to 0.9% at −25 V for exposed IDT SAW. However, for the buried IDT SAW, the tunability increases to the same level (0.9 %) from −12 V to 0 V, a significant reduction in the required gate voltage. In the buried IDT structure, the acoustic wave is directly traveling through the tuning layer, and the acoustic-electric interaction is enhanced, thus increasing the overall tunability and reducing the required biasing voltage. The measured SAW attenuation of the two devices are shown in Fig. 5b. The maximum attenuation for the devices with exposed and buried IDT are 1.1 dB/mm and 0.6 dB/mm, respectively. The reduced amplitude of attenuations could be attributed to the smaller total loss of the buried IDT structure. In the buried IDT structure, the patterned n-ZnO is isolated from the neighboring IDT regions, removing a possible charge leakage path which exists in the exposed IDT devices. The increased tunability range for lowered bias voltage and expanded linear tuning range are particularly desirable in portable and lower power consumption smart systems. Moreover, the device can be inserted in an oscillator circuit as a feedback phase element to form a frequency tunable oscillator.

**Conclusions**

In conclusion, we have demonstrated a voltage-tuned SAW phase shifter using the NZO/n-ZnO/GaN/Al2O3 multilayer structure. The
optimized piezoelectric NZO/n-ZnO/GaN layer structure provides over GHz frequency SAW response and wide frequency tuning due to the interaction between the SAW generated electric field in the piezoelectric layer and the free carriers in the semiconducting layer. Two device configurations are designed by placing the IDT at the different locations: the device with exposed IDT and with buried IDT. Compared with exposed IDT structure, the buried IDT configuration reduces overall ohmic loss and improves the signal to noise ratio from 13 dB to 41 dB. It also enhances the frequency tunability from 0.6% to 0.9% at lower biasing voltage range (−12 V, 0 V), and increases the center frequency from 1.25 GHz to 1.35 GHz. The voltage tunable SAW presents promising potential in adaptive and reconfigurable low power mobile platforms including programmable RFID and IoT.

Acknowledgment
The authors thank Veeco Instruments Inc. for providing GaN samples. This work was supported by the National Science Foundation under grant No. ECS-1002178. A part of the research was carried out at the Center for Functional Nanomaterials, Brookhaven National Laboratory, which is supported by the US Department of Energy, Office of Basic Energy Sciences, under Contract No DE-AC02-98CH10886.

References
1. C. Campbell, Surface acoustic wave devices for mobile and wireless communications, p. 631, Academic Press, Boston, MA, (1998).
2. M. Chin, B. Buford, and P. Dhagat, Journal of Applied Physics, 109, 07E332 (2011).
3. D. C. Malocha, M. Gallagher, B. Fisher, J. Humphries, D. Gallagher, and N. Kozlovska, Sensors (Switzerland), 13, 5897 (2013).
4. M. Asad and M. H. Sheikh, Sensors and Actuators B: Chemical, 198, 134 (2014).
5. K. Chang, F. Wang, Y. Ding, F. Pan, F. Li, S. Jia, W. Lu, S. Deng, J. Shi, and M. Chen, Biosensors and Bioelectronic, 54, 151 (2014).
6. L. Fan, H. Ge, S. Y. Zhang, H. Zhang, and J. Zhu, Sensors and Actuators, B: Chemical, 161, 114 (2012).
7. R. M. Hays and C. S. Hartmann, Proceedings of the IEEE, 64, 652 (1976).
8. M. Chomiki, in 2005 European Microwave Conference, vol. 33, p. 4 pp.-pp.1990, IEEE (2005).
9. H. Zhou, A. Talbi, N. Tiercelin, and O. Bou Matar, Applied Physics Letters, 104, 114101 (2014).
10. M. Pjoljat, C. Deguet, C. Billard, D. Mercier, A. Reinhardt, M. Aid, S. Ballandras, and E. Delay, Applied Physics Letters, 98, 232902 (2011).
11. J. Zhu, Y. Chen, G. Saraf, N. W. Emanetoglu, and Y. Lu, Applied Physics Letters, 89, 103513 (2006).
12. J. Pedrofs, F. Calle, R. Cuerdo, J. Grajal, and Z. Bougrioniou, Applied Physics Letters, 96, 123505 (2010).
13. R. Li, P. I. Reyes, S. Ragavendiran, H. Shen, and Y. Lu, Applied Physics Letters, 107, 73504 (2015).
14. A. Wixforth, J. Scriba, M. Wassermeier, J. Kotthaus, G. Weimann, and W. Schlapp, Physical Review B, 40, 7874 (1989).
15. Y. Chen, G. Saraf, Y. Lu, L. S. Wielunski, and T. Siegrist, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 25, 857 (2007).
16. M. M. De Lima and P. V Santos, Reports on Progress in Physics, 68, 1639 (2005).
17. K. Inoue and K. Sato, Japanese Journal of Applied Physics, 37, 2909 (1998).
18. L. C. Popa and D. Weinstein, Solid State Sensors Actuators and Microsystems Workshop (Hilton Head 2014), 269 (2014).
19. A. Muller, I. Giangu, A. Stavrinidis, A. Stefanescu, G. Stavrinidis, A. Dinescu, and G. Konstantinidis, 36, 1299 (2015).
20. Suk-Hun Lee, I. Hwan-Hee Jeong, Sung-Bum Bae, Hyun-Chul Choi, Jung-Hee Lee, and Yong-Hyun Lee, IEEE Transactions on Electron Devices, 48, 524 (2001).
21. N. W. Emanetoglu, G. Patounakis, S. Liang, C. R. Gorla, R. Wittstruck, and Y. Lu, IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, 48, 1389 (2001).
22. Y. Chen, P. I. Reyes, Z. Duan, G. Saraf, R. Wittstruck, Y. Lu, O. Taratula, and E. Galoppini, Journal of Electronic Materials, 38, 1605 (2009).
23. A. H. Fahmy and E. L. Adler, Applied Physics Letters, 22, 495 (1973).