A Petri-Net Approach to Modular Supervision With Conflict Resolution for Semiconductor Manufacturing Systems

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***Abstract*—In a semiconductor manufacturing system, particular human operations may violate desired requirements and lead to destructive failure. For such human-in-the-loop systems, this paper proposes a supervisory framework which guarantees that manual operations meet required specifications so as to prevent human errors in operation using Petri nets. Moreover, a modular technique with an intersection mechanism is proposed in order to cope with the state-space explosion problem of large-scale systems. A rapid thermal process in semiconductor manufacturing systems is provided to show the practicability of the proposed approach.**

***Note to Practitioners*—This work was motivated by the requirement of remote monitoring and supervision of semiconductor manufacturing systems. In such human-in-the-loop and large-scale systems, certain human operations may violate desired safety requirements and result in catastrophic failure. Moreover, the overall complexity of most existing Petri net modeling and analysis approaches significantly increases with the size of the considered systems. This paper suggests a modular supervisory scheme for modeling and synthesis of supervisory agents using Petri nets. The proposed method contributes a promising tool for preventing abnormal operations from being carried out to semiconductor manufacturing systems which, if appropriately modified, may be also applied to other types of discrete event systems.**

***Index Terms*—Human-in-the-loop, modular supervision, Petri nets (PNs), rapid thermal processes, semiconductor manufacturing systems, supervisory control.**

I. INTRODUCTION

Recently, semiconductor manufacturing has been a rapidly growing industry and developed worldwide into a very attractive research area. It combines in a synergistic way the classical engineering disciplines of electronic, electrical, and mechanical engineering and computer science, leading to new kinds of products. One of the topics in semiconductor manufacturing is the investigation of the eManufacturing with the support of network-based monitoring and supervision. In the last decade, the most successful network developed has been the Internet that has proved a great potential for the high-level control of process plants. Internet-based control is a new concept. It received much attention as a basis for the possible next generation of control systems in recent years [1]–[5]. Typically, an Internet-based control system (remote access using Internet protocol (IP)-based networks) is a "human-in-the-loop" system since people use a general Web browser or specific software to monitor and control remotely located systems [5]. As shown in Fig. 1(a), a human operator is involved in the loop and sends control commands according to the observed status displayed by the state and/or image feedback. Also, human errors have a significant influence on system reliability, at times more than technological failures. Vineyard *et al.* [6] reported that based on empirical analysis from U.S. manufacturing plants, failures caused by improper human operator action accounted for 40% of all failures. This is more than any other failure types.

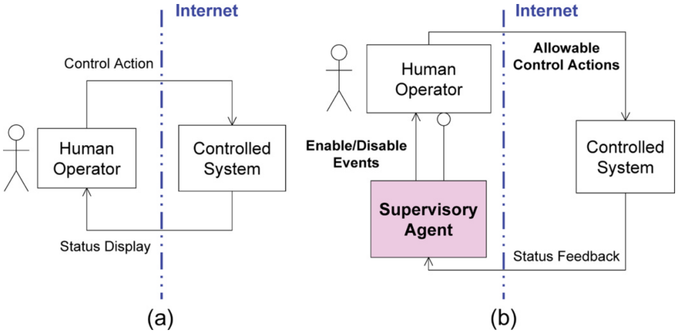

Fig. 1. (a) Typical remote control system with the human in the loop. (b) A remote supervisory control scheme [5].

Much research has been conducted to classify human errors and to develop a mechanism for their reduction. For such human-in-the-loop systems, Lee and Hsu [5] proposed for the first time to use the Petri net (PN)-based supervisory control theory (SCT) of discrete event systems (DESs) to develop supervisory agents so as to prevent abnormal operations from being carried out, as shown in Fig. 1(b). First, the supervisory agent acquires the system status and makes the decision to enable/disable the associated events to meet the required specifications, typically safety requirements. The human operator is then only allowed to perform the enabled events to control the system. The role of a supervisory agent is to interact with the human operator and the controlled system so that the closed human-in-the-loop system meets the required specifications and to guarantee that undesirable executions are never performed.

One issue of the SCT is the state-space explosion in large systems, i.e., the number of states in the global plant's model increases exponentially. A standard way to handle this problem is by modular supervision. In general, the specifications are only relevant to part of the plant. Hence, it is not necessary to consider the entire plant to synthesize its supervisor. In this paper, instead of a centralized supervisor synthesis for an entire plant, a modular supervisor is designed for each local plant (affected subsystems) according to a local specification. These modular supervisors are conceived as operating independently, each exercising control to satisfy its own specification. However, when all the modular supervisors operate concurrently, they may result in conflict. A critical situation is that the execution of certain operation considered to be safe by each supervisor may lead to a hazardous situation. Thus, this paper proposes to apply an intersection mechanism (i.e., AND logic) to such conflict resolution.

Fig. 2 shows the proposed scheme of the modular supervisory control for a remotely located system with the human in the loop. First, the individual supervisors issue the enable and disable actions based

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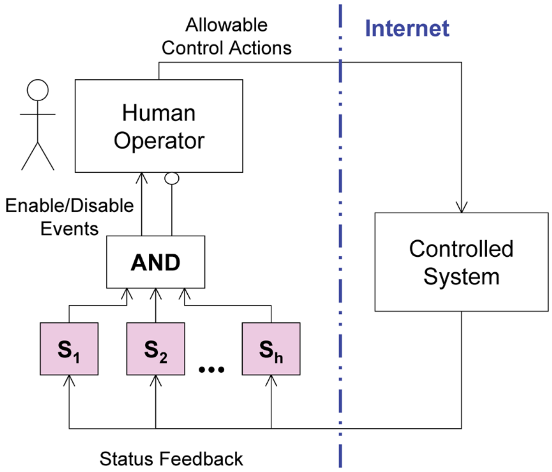


Fig. 2. The proposed modular supervision for remotely human control system.

on the acquired system status and on the respective h specifications according to which these supervisors are designed. Then, by applying the intersection mechanism, these actions are combined to have the decision to enable/disable associated controllable events. The human operator is then only allowed to perform those enabled events to control the system. A rapid thermal process (RTP) in semiconductor manufacturing systems is used to demonstrate the feasibility of the developed approach.

II. PETRI NETS (PNS) AND SUPERVISORY CONTROL

A. PN Concepts

A PN is identified as a particular kind of bipartite directed graph populated by three types of objects. They are places, transitions, and directed arcs connecting places and transitions. Formally, a PN can be defined as

$$G = (P, T, I, O), \tag{1}$$

where

$P = \{p_1, p_2, \ldots, p_m\}$	is a finite set of places, where $m > 0$;
$T = \{t_1, t_2, \ldots, t_n\}$	is a finite set of transitions with $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$, where $n > 0$;
$I : P \times T \rightarrow N$	is an input function that defines a set of directed arcs from P to T, where $N = \{0, 1, 2, \ldots\}$;
$O : P \times T \rightarrow N$	is an output function that defines a set of directed arcs from T to P.

A marked PN is denoted as (G, M_0), where $M_0 : P \rightarrow N$ is the initial marking. A transition t is enabled if each input place p of t contains at least the number of tokens equal to the weight of the directed arc connecting p to t. When an enabled transition fires, it removes the tokens from its input places and deposits them on its output places. PN models are suitable to represent the systems that exhibit concurrency, conflict, and synchronization.

Some important PN properties in manufacturing systems include boundedness (no capacity overflow), liveness (freedom from deadlock), conservativeness (conservation of non-consumable resources), and reversibility (cyclic behavior). The concept of liveness is closely related to the complete absence of deadlocks. A PN is said to be live if, no matter what marking has been reached from the initial marking, it is possible to ultimately fire any transition of the net by progressing through some further firing sequences. This means that a live PN guarantees deadlock-free operation, no matter what firing sequence is chosen. Validation methods of these properties include reachability analysis, invariant analysis, reduction method, siphons/traps-based approach, and simulation [7].

B. Supervisor Synthesis

Definition 2.1: Given two nets $G_1 = (P_1, T_1, I_1, O_1)$ and $G_2 = (P_2, T_2, I_2, O_2)$ with initial marking $M_{0,1}$ and $M_{0,2}$, respectively. The synchronous composition of G_1 and G_2 is a net $G = (P, T, I, O)$ with initial marking M_0

$$G = G_1 \| G_2 \tag{2}$$

where

$P \quad = P_1 \cup P_2;$

$T \quad = T_1 \cup T_2;$

$I(p, t) \quad = I_i(p, t)$ if $(\exists i \in \{1, 2\})[p \in P_i \wedge t \in T_i]$, else $I(p, t) = 0;$

$O(p, t) \quad = O_i(p, t)$ if $(\exists i \in \{1, 2\})[p \in P_i \wedge t \in T_i]$, else $O(p, t) = 0;$

$M_0(p) \quad = M_{0,1}(p)$ if $p \in P_1$, else $M_0(p) = M_{0,2}(p)$.

An agent that specifies which events are to be enabled and disabled when the system is in a given state is called a supervisor. For a system with plant model G and specification model H, the supervisor can be obtained by synchronous composition of the plant and the specification models

$$S = G \| H \tag{3}$$

where the transitions of H are a subset of the transitions of G, i.e., $T_H \in T_G$. Note that S obtained through the above construction, in the general case, does not represent a proper supervisor, since it may contain deadlock states from which a final state cannot be reached. Thus, the behavior of S should be further refined and restricted by PN analysis [8].

III. SYNTHESIS OF MODULAR SUPERVISORS

A. Modular Plants

A PN is identified as a particular kind of bipartite directed graph populated by three types of objects. They are places, transitions, and directed arcs connecting places and transitions. A PN can be used to describe a system to be controlled, which is usually composed of modular subsystems. Formally, each subsystem $i \in \{1, 2, \ldots, g\}$ can be modeled by a PN G_i. The global unsupervised plant is obtained by composing all the subsystems $G = \|_{i=1}^{g} G_i$. It is easy to see that the number of states in the global plant's model increases exponentially with g, the number of modular components. This fact is crippling when it comes to computation for realistic systems. This issue is known as state-space explosion, and is currently an area of intensive research in the formal verification of DESs.

B. Modular Specifications

The specification is typically given as a collection of forbidden states (such as resource conflicts, deadlocks, and buffer overflow), each of which represents a desired requirement of the controlled system. These subspecifications can be composed to yield a global specification, $H = \|_{i=1}^{h} H_i$, where we have h specifications. However, this procedure is subject to state-space explosion just as in the case of a modular plant.

C. Modular Supervisors

Fortunately, in the case of modular specification, the principles of modular synthesis outlined in [9] can be applied. In general, the specifications are only relevant to part of the plant, so it is not necessary to consider the entire plant for synthesizing the supervisor. However, when all the modular supervisors operate concurrently, they may turn out to be in conflict. A critical situation is that the execution of certain operation considered to be safe by each supervisor may be hazardous globally. Thus, this paper applies the intersection mechanism (i.e., AND logic) to such conflict resolution

$$S = \bigcap_{i=1}^{h} S_i. \tag{4}$$

In (4), $Si = G_{Hi} \| H_i$, where G_{Hi} means the subplants (part of the entire plant) affected by H_i.

The supervisor synthesis problem is solved for each modular specification and then the resulting supervisors are integrated to form a solution to the globally specified problem. In addition to being more easily synthesized (with several smaller state spaces), a modular supervisor is easier to modify, update, and maintain. For example, if one subspecification is changed, then it is only necessary to redesign the corresponding subsupervisor, instead of the entire supervisor. The design procedure of a modular supervisor consists of the following steps.

Step 1) Construct the PN model of each controlled subsystem.
Step 2) Construct the PN model of each required subspecification.
Step 3) Based on each subspecification, compose it with the affected subsystems to synthesize each subsupervisor, respectively.
Step 4) Verify and refine each subsupervisor to a live and bounded model.
Step 5) Integrate the supervisors by the intersection mechanism to form a modular supervisor.

To verify and refine each subsupervisor in Step 4, based on PN models, reachability analysis, invariant analysis, reduction method, siphons/traps-based approach, and simulation [7] could be applied. In this paper, the software package ARP [10] is chosen to verify the behavioral properties liveness and boundedness using the reachability analysis.

IV. APPLICATION EXAMPLE

An application of a RTP controlled over the Internet in a semiconductor manufacturing system is provided to illustrate the proposed approach.

A. Description of the RTP System

A rapid thermal processor is a relatively new semiconductor manufacturing device [11]. Rapid thermal processing is conducted on silicon wafers in a high-temperature oven using high-wattage halogen lamps. The gas and heat combine to accelerate the formation of an oxide or nitride layer on the wafer. RTP is also used to create layers of epitaxial silicon on the silicon substrate. The unit can be applied to the ion implantation, polysilicon annealing, oxide reflow, silicide formation, and contact alloying.

An RTP schematic diagram is shown in Fig. 3, which is composed of: 1) a reaction chamber with a door; 2) a robot arm for wafer loading/unloading; 3) a gas supply module with a mass flow controller and pressure controller-I; 4) a heating lamp module with a temperature controller; and 5) a flush pumping system with a pressure controller-II. The initial state of the components in the RTP is either closed or off, except that the door is open. A realistic "recipe" of the hydrogen bake process is as follows.

Step 1) Load the raw wafer.
Step 2) Close the chamber door.
Step 3) Open the gas valve to supply gases with a desired gas flow rate and pressure of 2.8 liters per minute (lpm) and 0.5 Torr, respectively.
Step 4) Close the gas valve.
Step 5) Turn on the heating lamp to bake the wafer with a desired baking temperature and duration of 1000 $^\circ$C and 4 s, respectively.
Step 6) Turn off the heating lamp.
Step 7) Turn on the flush pump with a desired pressure of less than 0.05 Torr.
Step 8) Turn off the flush pump.
Step 9) Open the chamber door.
Step 10) Unload the processed wafer.

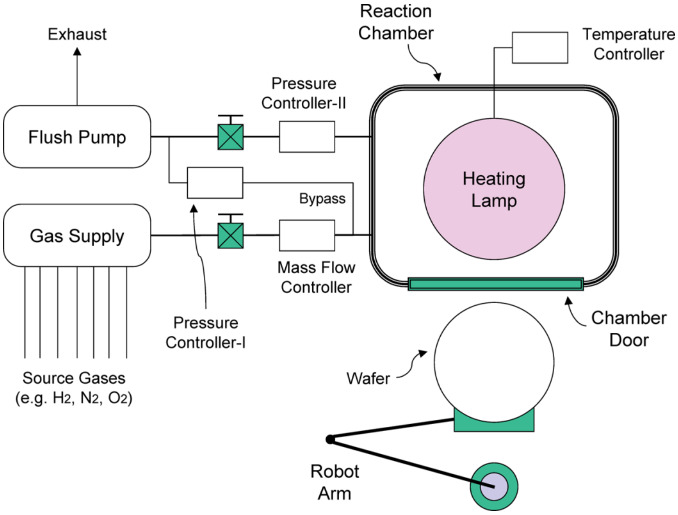


Fig. 3. A rapid thermal processor.

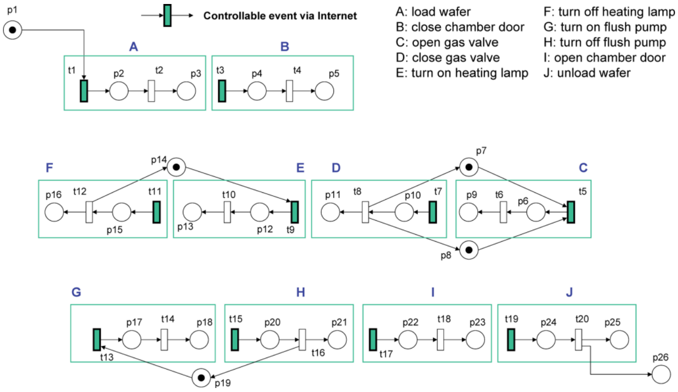


Fig. 4. The plant model with ten human operations.

B. Modeling of Modular Plants

By applying the task-oriented concept, modular PN models of the RTP is constructed, as shown in Fig. 4, which consists of 26 places and 20 transitions, respectively. Letters A–J represent ten remote controllable operations for the RTP system. Corresponding notations are described in Table I. Transitions drawn with dark symbols are events that are controllable by remote clients via the Internet.

C. Synthesis of Modular Supervisors

The following safety specifications must be enforced throughout system operation.

TABLE I
NOTATIONS FOR THE PN MODEL IN FIG. 4

Place	Description	Transition	Description
p1	Raw wafer buffer	t1	Cmd: start loading wafer
p2	Loading wafer	t2	Re: end loading wafer
p3	Loading wafer completed	t3	Cmd: start closing chamber door
p4	Closing chamber door	t4	Re: end closing chamber door
p5	Closing chamber door completed	t5	Cmd: start opening gas valve
p6	Opening gas valve	t6	Re: end opening gas valve
p7	Mass flow controller ready	t7	Cmd: start closing gas valve
p8	Pressure controller-I ready	t8	Re: end closing gas valve
p9	Opening gas valve completed	t9	Cmd: start turning on heating lamp
p10	Closing gas valve	t10	Re: end turning on heating lamp
p11	Closing gas valve completed	t11	Cmd: start turning off heating lamp
p12	Turning on heating lamp	t12	Re: end turning off heating lamp
p13	Turning on heating lamp completed	t13	Cmd: start turning on flush pump
p14	Temperature controller ready	t14	Re: end turning on flush pump
p15	Turning off heating lamp	t15	Cmd: start turning off flush pump
p16	Turning off heating lamp completed	t16	Re: end turning off flush pump
p17	Turning on flush pump	t17	Cmd: start opening chamber door
p18	Turning on flush pump completed	t18	Re: end opening chamber door
p19	Pressure controller-II ready	t19	Cmd: start unloading wafer
p20	Turning off flush pump	t20	Re: end unloading wafer
p21	Turning off flush pump completed		
p22	Opening chamber door		
p23	Opening chamber door completed		
p24	Unloading wafer		
p25	Unloading wafer completed		
p26	Processed wafer buffer		

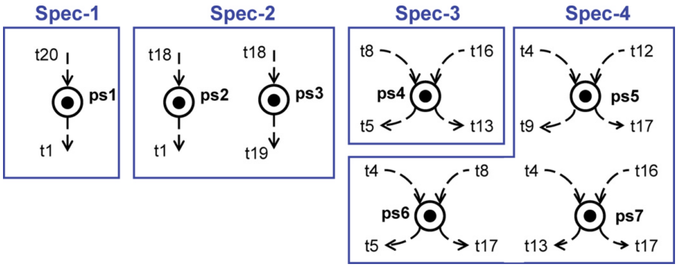


Fig. 5. The supervisor models for four specifications with seven supervisory places.

Spec-1: Wafer Loading is allowed only when no wafer is in the chamber.

Spec-2: Wafer Loading/unloading is allowed only when the door is open.

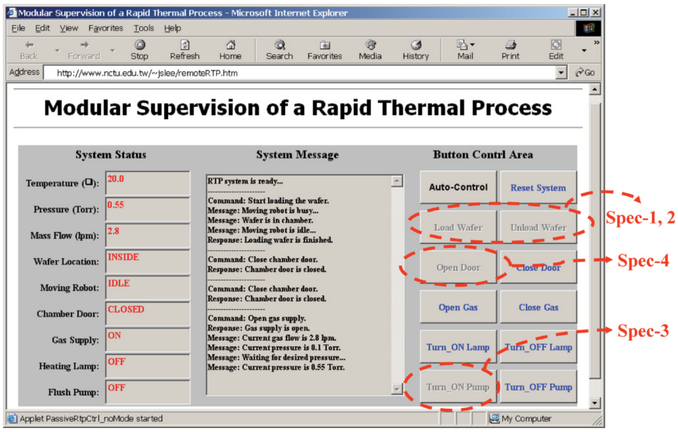
Spec-3: The gas valve must be closed when the flush pump is applied to the chamber.

Spec-4: The gas valve, heating lamp, and flush pump cannot be started when the door is open.

According to the four modular specifications, the supervisory places are designed, as shown in Fig. 5, where **ps1-7** (**ps1** for Spec-1, **ps2-3** for Spec-2, **ps4** for Spec-3, and **ps5-7** for Spec-4) are used to prevent undesired and unsafe operations on the part of the human operator. Corresponding notations for the supervisory places are described in Table II. A supervisory place is modeled as an input place of the transitions that require such a condition, and as an output place of those that reset this condition. Take an example of **ps4** for Spec-3, it physically means the gas valve is closed or the flush pump is turned off. The place **ps4** makes two transitions $t5$ (open the gas valve) and $t13$ (turn on the flush pump) mutually exclusive. Intuitively, performance of $t5$ is only allowed if the flush pump is turned off and $t13$ has not yet been fired. If $t13$ has been fired, $t5$ cannot be executed until $t16$ (end turning off the flush pump) is given to signal that the flush pump is turned off. Thus, the gas valve must be closed when the flush pump is applied to the chamber.

TABLE II
NOTATIONS FOR SUPERVISORY PLACES IN FIG. 5

Place	Description
ps1	Spec-1: chamber is empty
ps2	Spec-2: chamber door is open
ps3	Spec-2: chamber door is open
ps4	Spec-3: gas is closed/pump is off
ps5	Spec-4: door is closed/lamp is off
ps6	Spec-4: door is closed/gas is closed
ps7	Spec-4: door is closed/pump is off



http://www.nctu.edu.tw/~jslee/remoteRTP.htm

Modular Supervision of a Rapid Thermal Process

System Status

Temperature (□): 20.0
Pressure (Torr): 0.55
Mass Flow (lpm): 2.8
Wafer Location: INSIDE
Moving Robot: IDLE
Chamber Door: CLOSED
Gas Supply: ON
Heating Lamp: OFF
Flush Pump: OFF

System Message

```
RTP system is ready...
---------------------
Command: Start loading the wafer.
Message: Moving robot is busy...
Message: Wafer is in chamber.
Message: Moving robot is idle...
Response: Loading wafer is finished.
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Command: Close chamber door.
Response: Chamber door is closed.
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Command: Close chamber door.
Response: Chamber door is closed.
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Command: Open gas supply.
Response: Gas supply is open.
Message: Current gas flow is 2.8 lpm.
Message: Current pressure is 0.1 Torr.
Message: Waiting for desired pressure...
Message: Current pressure is 0.55 Torr.
```

Button Contrl Area

Applet PassiveRtpCtrl_noMode started

Fig. 6. Four command buttons are disabled at Step 3 to meet the specifications.

At this stage, due to its ease of manipulation, support for graphics import, and ability to perform structural and performance analyses, the software package ARP [10] is chosen to verify the behavioral properties of each PN model. The validation results reveal that the present models are live and bounded. The liveness property means that the system can be executed properly without deadlocks, while the boundedness property means that the system can be executed with limited resources (e.g., limited buffer sizes).

D. *Implementation of the Modular Supervisor*

The system modeling and design developed in previous stages provide supervisory control models for implementation. This paper applies Java to realize the present remote monitoring and control technology. Fig. 6 shows the developed web pages as human-machine interface (HMI) for human operators who can be far away from the actual RTP location. According to the current states, the supervisory agent disables several controllable buttons so as to meet the specifications. Thus, the safety requirements of the RTP processing are guaranteed as human operations are conducted. It is believed that the proposed approach would be also beneficial to the HMI design.

V. CONCLUSION

This paper presents a PN-based framework for designing and implementing the modular supervisor for Internet-based control systems. Each subsupervisor is systematically synthesized and then integrated by the intersection mechanism. According to the feedback status of a remotely located system, the developed modular supervisor provides allowable commands for human operators by disabling those that violate specifications.

One main problem in a modular control scheme is that the intersection mechanism of each deadlock-free subsupervisor cannot ensure the liveness property of the closed-loop behavior. That means under joint control of two (or more) deadlock-free supervisors may be deadlocked. Only under a special condition can a global deadlock-free supervisor be obtained in modular synthesis scheme [9]. Hence, several approaches to this issue have been proposed [12], [13]. Also, to efficiently design the supervisory places, the supervision based on place invariants [14] technique could be further employed especially when the specifications are more complex. The recently proposed elementary siphon concept and theory can be used to reduce significantly the number of supervisory places [15]–[20]. Theory of regions and its variation can be used to design optimal and almost optimal Petri net supervisors [20]–[23]. Future work will integrate these approaches into the presented modular framework. It should also pursue for the application of the presented approach to industrial-size systems [19], [24]–[27].

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